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## INFORMATION TECHNOLOGIES AND TRAVEL

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VRIJE UNIVERSITEIT

**Information Technologies and Travel**

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad Doctor aan  
de Vrije Universiteit Amsterdam,  
op gezag van de rector magnificus  
prof.dr. F.A. van der Duyn Schouten,  
in het openbaar te verdedigen  
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door

Sergejs Gubins

geboren te Riga, Letland

promotor: prof.dr. E.T. Verhoef  
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# Contents

<b>List of figures</b>	<b>iii</b>
<b>List of tables</b>	<b>v</b>
<b>List of abbreviations and symbols</b>	<b>vi</b>
<b>Preface</b>	<b>xi</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Motivation	1
1.2 Information technologies in transport	3
1.3 Road pricing	7
1.4 Overview of the thesis	10
<b>2 Teleworking and congestion: A dynamic bottleneck model</b>	<b>13</b>
2.1 Introduction	13
2.2 Teleworking within Vickrey's dynamic bottleneck model	15
2.3 Marginal willingness to pay for and externalities of teleworking technologies	21
2.4 Supply of teleworking technologies	26
2.5 Teleworking with the first-best road toll	33
2.6 Summary and conclusions	35
Appendix	38
<b>3 Dynamic bottleneck congestion and residential land use in the monocentric city</b>	<b>45</b>
3.1 Introduction	45
3.2 Model setup	48
3.3 Solution of the model	54
3.4 Unpriced market equilibrium	60
3.5 City with first-best road pricing	62
3.6 Sensitivity analysis and other policies	70
3.7 Summary and conclusions	72

<b>4</b>	<b>Welfare effects of road pricing and traffic information under alternative ownership regimes</b>	<b>75</b>
4.1	Introduction	75
4.2	Model	77
4.3	Pricing	82
4.4	Numerical simulations	92
4.5	Sensitivity analysis	98
4.6	Summary and conclusions	101
<b>5</b>	<b>Teleworking technologies and travel</b>	<b>105</b>
5.1	Introduction	105
5.2	Methodology	109
5.3	Empirical analysis	115
5.4	Sensitivity analysis	122
5.5	Conclusions	123
	Appendix	125
<b>6</b>	<b>Conclusions</b>	<b>127</b>
6.1	Summary	127
6.2	Policy implications	131
6.3	Future research	132
	<b>References</b>	<b>135</b>
	<b>Nederlandstalige samenvatting (summary in Dutch language)</b>	<b>145</b>

## List of figures

2.1	Utility structure and opportunity costs for a driver in the conventional representation of Vickrey's dynamic bottleneck model	17
2.2	Equilibrium isocost function with homogeneous drivers	19
2.3	Isocost functions of the heterogeneous drivers, if equipped drivers arrive at work late	22
2.4	Marginal willingness to pay for teleworking technologies	24
2.5	Parameter combinations that correspond to an above-optimal level of teleworking penetration under perfect competition, $\gamma = 1$	29
2.6	Parameter combinations that have a larger total social welfare under monopoly than under perfect competition, $\gamma = 1$	32
2.7	Isoprice function of the homogeneous drivers	34
2.A	Isocost functions of the heterogeneous drivers, if equipped drivers arrive at work late and early	39
3.1	Example of a morning schedule	50
3.2	Utility structure and opportunity costs of a driver $i$	51
3.3	Consumption of land by residential location (base equilibrium)	60
3.4	Population density by residential location (base equilibrium)	61
3.5	Rents by residential location (base equilibrium)	61
3.6	Travel patterns by residential location in an unpriced market equilibrium	62
3.7	Consumption of land by residential location [with pricing (solid) and without (dashed)]	66
3.8	Population density by residential location [with pricing (solid) and without (dashed)]	67
3.9	Rents by residential location [with pricing (solid) and without (dashed)]	67
3.10	Road toll by residential location	68
3.11	Travel patterns by residential location with the first-best road pricing	69
3.12	Utility by various bottleneck capacity levels	71
3.13	City size for various bottleneck capacity levels	71



4.1a	Demand and stochastic costs of travel	81
4.1b	Willingness to pay for information	81
4.1c	Demand for information	81
4.2	Demand for (bold line) and marginal revenue (dash line) of information	83
4.3	A road operator profits under various tolls when information is free	85
4.4	A hypothetical road operator profit function $\Pi(\tau)$ when information is free	85
4.5	Reaction function of the information provider	86
4.6a	Willingness to pay for information when the road toll increases from $\tau = d - C^1$ (regular line) to $\tau = \tilde{\tau}$ (bold line)	87
4.6b	Demand for (solid line) and $MR$ of (dashed line) information when the road toll increases from $\tau = d - C^1$ (regular line) to $\tau = \tilde{\tau}$ (bold line)	87
4.7	Possible reaction functions of an information provider and a road operator	90
4.8a	Relative efficiency of the market setups as a function of the delay probability $p$ , under constant expected cost $E(C)$	99
4.8b	Relative efficiency of the market setups as a function of the delay probability $p$ , under constant expected cost $E(C)$	99
4.9a	Relative efficiency of the market setups as a function of travel demand elasticity $e$	100
4.9b	Relative efficiency of the market setups as a function of travel demand elasticity $e$	100
5.1	Identification strategy	113
5.2	Commuting distances in 1996 and 2010	117
5.A	Share of teleworkers within professions in 2010	126

## List of tables

4.1	Subsections of this chapter that correspond to a particular pricing strategies combination	82
4.2	Alternative ownership regimes	93
4.3	Characteristics of various market arrangements based on the baseline numerical estimations	96
5.1	Logit estimates whether an employee works in 2010	119
5.2	Balancing tests	120
5.3	Commuting distance, <i>causal effect</i>	121
5.4	Commuting distance within teleworking professions, <i>non-causal effect</i>	121
5.5	Robustness checks of matching results for commuting distance	123
5.A	Descriptive statistics	125

# List of abbreviations and symbols

## Chapter 2

$ICT$	information and telecommunication technologies
$\alpha$	value of travel delay
$\beta$	value of schedule delay when arriving early at work, i.e., before $t^*$
$\gamma$	value of schedule delay when arriving late at work, i.e., after $t^*$
$\Delta$	increase in marginal utility value of being at home due to teleworking technology
$s$	capacity of a traffic bottleneck
$t^*$	preferred time of arrival at work
$t_q$	time of arrival at work of the first driver
$t_{q'}$	time of arrival at work of the last driver
$t_S$	time when the morning period starts
$t_F$	time when the morning period finishes
$\bar{N}$	total number of car drivers
$N_e$	number of equipped drivers
$N_u$	number of unequipped drivers
$N_e^L$	number of equipped drivers who arrive at work after $t^*$
$N_e^E$	number of equipped drivers who arrive at work before $t^*$
$N_u^L$	number of unequipped drivers who arrive at work after $t^*$
$N_u^E$	number of unequipped drivers who arrive at work before $t^*$
$N_e^\#$	threshold number of equipped drivers
$N_e^{FB}$	number of equipped drivers in social optimum (first-best)
$N_e^{PC}$	number of equipped drivers under perfect competition
$N_e^M$	number of equipped drivers under monopoly
$H$	marginal utility of being at home
$W$	marginal utility of being at work
$V$	marginal utility of being in a vehicle
$\Gamma$	ideal utility level which a driver can reach over the course of the morning

$\Gamma_e$	ideal utility level of a driver who is equipped with the teleworking technology
$\Gamma_u$	ideal utility level of a driver who is unequipped with the teleworking technology
$U$	utility level of a driver
$U_e$	utility of a driver who is equipped with the teleworking technology
$U_u$	utility of a driver who is not equipped with the teleworking technology
$P(t)$	generalized travel costs when arriving at work at time $t$
$P_e$	generalized travel costs of a driver who is equipped with the teleworking technology
$P_u$	generalized travel costs of a driver who is not equipped with the teleworking technology
$MWTP$	marginal willingness to pay
$T(t)$	travel delay when arriving at work at time $t$
$MSB$	marginal social benefit
$MSB_e$	marginal social benefit of equipped drivers
$MSB_u$	marginal social benefit of unequipped drivers
$MSB_L$	marginal social benefit when the number of equipped drivers is below $N_e^\#$
$MSB_H$	marginal social benefit when the number of equipped drivers is above $N_e^\#$
$TSB$	total social benefit
$TSB^{PC}$	total social benefit under perfect competition
$TSB^{FB}$	total social benefit in social optimum (first-best)
$TSB^M$	total social benefit under monopoly
$\Pi^M$	profit of a monopolist
$MR$	marginal revenue
$MR_L$	marginal revenue when the number of equipped drivers is below $N_e^\#$
$MR_H$	marginal revenue when the number of equipped drivers is above $N_e^\#$

### Chapter 3

$CBD$	central business district
$\alpha$	value of travel delay
$\beta$	value of schedule delay when arriving early at work, i.e., before $t^*$
$\gamma$	value of schedule delay when arriving late at work, i.e., after $t^*$
$s$	capacity of a traffic bottleneck
$t^*$	preferred time of arrival at work
$t_q$	time of arrival at work of the first driver
$t_{q'}$	time of arrival at work of the last driver
$t_S$	time when the morning period starts
$t_F$	time when the morning period finishes
$t_d$	time of departure from home
$t_a$	time of arrival at work
$Z$	distance from the central business district
$\bar{Z}$	distance from the central business district to city boundary
$T_{FF}$	free-flow travel time needed to cover one unit of distance
$T_q$	travel delay
$H$	marginal utility of being at home
$W$	marginal utility of being at work
$V$	marginal utility of being in a vehicle
$\Gamma$	ideal utility level which a driver can reach over the course of the morning
$U$	utility level of a driver
$m$	wage
$n$	total number of city inhabitants
$X$	utility from time spent in the morning
$Q$	numeraire good
$w$	marginal utility of being early at work, i.e., before $t^*$
$L$	consumption of land
$\underline{L}$	minimum level of land consumption within the city
$\bar{L}$	maximum level of land consumption within the city
$r$	land rent
$\varepsilon$	parameter that keeps the marginal utility of being at home above that of being at work

$\varphi$	parameter that “converts” the amount of land consumed into marginal utility of being at home
$i$	driver
$C$	congestion cost
$C^{FB}$	first-best generalized price for road use
$\theta$	the weighted factor
$\theta^{FB}$	the weighted factor in the first-best
$\chi$	lump-sum monetary transfer from the government to the drivers
$\tau$	first-best time-dependent road toll
$b$	exponent for time component in the Cobb-Douglas utility function

## Chapter 4

$ICT$	information and telecommunication technologies
$ATIS$	advanced traveler information systems
$n$	number of parallel routes
$D^T$	inverse demand for travel
$N$	number of drivers
$j$	driver
$N_j$	number of drivers with a higher travel benefit than driver $j$
$C^0$	cost of the trip without delay
$\bar{C}^0$	cost of the trip with delay
$p$	probability of a delay on a single route
$E(C)$	expected travel cost
$wtp^I$	willingness to pay for information
$\pi$	price of information
$\pi^{max}$	reservation price of information
$MC$	marginal cost
$MR$	marginal revenue
$\pi^*$	profit-maximizing price of information
$\tau$	road toll
$\Pi$	profit
$\gamma$	road subsidy to drivers
$\delta$	information subsidy to drivers
$e$	travel demand elasticity
$\omega$	relative efficiency

$welfare_i$	social welfare in the market setup $i$
$welfare_{ref}$	social welfare in the reference market
$welfare_{fb}$	social welfare under first-best market conditions

## Chapter 5

$OLS$	ordinary least squares
$ATIS$	advanced traveler information systems
$Y_j$	commuting distance of an individual
$j$	profession type
$E$	expectation operator
$d$	treatment dummy
$t$	year of observation
$s$	share of non-teleworking employees within teleworking professions
$\alpha_0$	effect of technology on commuting distance of teleworkers within teleworking professions
$\alpha_1$	effect of technology on commuting distance of non-teleworkers within teleworking professions

## Preface

This book is a somewhat imperfect reflection of my six-year-long effort to grasp the workings of academic research. Here I contribute a few bits to an already impressive body of knowledge about travel and travelers. My attempt is humble and well-intentioned. But to complete the story of this thesis I have to spotlight at least some people who made my PhD a successful experience!

Science is sometimes perceived as a tranquil affair, but I would rather compare it to a rollercoaster in which staying calm is a skill one has to master over time. For example, once, at the beginning of my PhD, the third paragraph on page 86 caused me a sleepless night when I thought I have found a critical error in a paper which was almost finished. Next morning all derivations turned out to be correct again, after a few insightful remarks from my advisor and a more careful second thought. My advisor Erik Verhoef is a person to whom I owe the largest debt of gratitude for guiding me through the ups and downs on the way to this thesis. He stoically tolerated my mumblings during the meetings, mistakes in analysis, and periods of “no results”. Erik’s thoughtful and to-the-point suggestions, sprinkled with a lifeful sense of humor, eventually led to a several joint papers which, I hope, are worth the pain endured. Thank you, Erik! I also thank my co-advisor Thomas de Graaff for his help and good discussions, sometimes on the way to various meetings! Furthermore, I am grateful to my co-author Jos van Ommeren for his kind and enlightening ways of sharing the craft of an empirical analysis!

Thanks to all members of my defense committee, Caspar Chorus, Robin Lindsey, Hans van Lint, Jan Rouwendal and Harry Timmermans for the willingness to read and judge this dissertation, which is not an easy task! Caspar and Harry followed the progress of this dissertation during TRISTAM project get-togethers and I appreciate comments they brought on the way!

I had a pleasure to meet Robin Lindsey on several occasions. He once assumed a memorable, but scary role, when, during my conference presentation of chapter 2, he gave a remark that made me think that the model I presented has been already studied and published... Later it appeared that the comment referred to his much more ambitious work still in progress which is



only slightly related to my stylized model. I am honored that Robin, one of the fathers of a research framework I use in this book, joins the committee!

Many people shaped this thesis in some way. But two men, one at the time just before PhD and another at the very end of it, helped me a lot. I thank Henri de Groot, my master thesis advisor, for his wonderful lectures and gentle guidance, especially after one meeting when he told me I have to rewrite my master thesis entirely. This served me well! I am also obliged to Lanfranco Senn from Bocconi University for good working conditions that let me finish this overdue thesis as a CERTeT postdoctoral researcher already in Milan.

Last, but not least, my endeavor would not be possible academic-wise without two Latvian economists, Mihail Hazan and Morten Hansen, both of whom inspired me, in their quite different ways, to study economics. While Mihail gave an exciting first glimpse on the way scientists work, Morten has been the most passionate teacher I have ever learnt from. EuroFaculty courses at the University of Latvia were a pure intellectual delight.

Collegial and cheerful atmosphere of the Department of Spatial Economics led by late Piet Rietveld generated an ideal backdrop for my entire stay in Amsterdam. I thank all department members for nice discussions and chitchats during the ever-important coffee breaks and collective lunches! When I have joined the department, a few students, including me, were ~~kicked out~~ moved, due to the space shortage, from the 4<sup>th</sup> to the 14<sup>th</sup> floor to facilitate “high-level” research (with a later downgrade to the 5<sup>th</sup> floor). This proved to be a perfect arrangement as I was lucky to work around wonderful people!

I am happy to be a friend of Aart, my paranymp, whose funny and crazy and bigger-than-life personality often unleashes in a surprising way! Our cycling adventures in Yukon and British Columbia and other less challenging times together left strong impressions on me. I am always keen to learn your unique view on the world! Jessie, also my paranymp, has shared an office with me and unwittingly witnessed most of this book on a whiteboard in front of her. I have enjoyed our many discussions about the Dutch way of living, and I admire your unapologetically pragmatic and kind approach to life. Hans, whose imposing research and squash skills are hard to match, is a perfect colleague with whom I always had fun sharing thoughts about new ideas and recently finished lunch seminars. Many thanks to great Stefanie, Ceren, Martin and all the people who have joined and left the group of the 14<sup>th</sup>/5<sup>th</sup> floor at various points in time! I hope to catch your positive vibes in the future as well!

This thesis does not contain a few brilliant chapters, for example, about radio traffic information or a parking app, because they have never been written, either due to the lack of data or properly nurtured ideas. Also a paper on Columbian terrorist attacks, proposed as joint work by Michiel, whose well-mannered and intelligent company I value a lot, did not materialize, though he might still write it someday. But I did enjoy our after-work drinks at the Zuidas!

Amsterdam, beautiful biking paradise, has started for me with the STREEM master program at the VU. I am very grateful to the fellow master students, in particular to Andreas, Annika, Filka and Franziska, for cooperative and enjoyable time together! Andrzej and the rest of the crowd from Uilenstede, people of Soembawastraat and many others gave an essential flavor to the city. Visits to Concertgebouw and Café Gollem, the Ronde Hoep cycling and squash sessions at Zuiver – thanks for these and others moments of friendly relations!

In my hometown Riga, which I faithfully visit at least twice a year, I am always happy to meet my school friends Boris, Lev, Sergey and Zhenja! These meetings are even more precious as we scatter around the globe!

I thank my close relatives, Zoja, Inna, Samuel, Anna, Michael and Ariela for frequently hosting and always pampering me! I trust we see many sunny days ahead! I especially want to mention my grandmothers, Elena and Zoja, who show heart-warming interest in whatever I do! I will visit more often!

My parents, Marina and Jurij, and brother Ilja, is my secret source of strength, joy and occasional epiphanies. It seems unfair that my parents do not get any official recognition for following all the struggles of each idea that I had to share with them. They were often the first to test my wild research dreams with the common sense. Above all, their unconditional support helped me to get through and made this PhD possible. Thank you!

Sergej

Milan, December 2014



# 1 Introduction

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## 1.1 Motivation

Over the last century travel has become faster, safer, more energy efficient, more reliable and comfortable, moreover, it turned out to be much cheaper.<sup>1</sup> These improvements were often caused by a general progress in science and engineering. Recent developments in information technologies further enhanced travel convenience by, for example, allowing car drivers to follow complex routes via satellite navigation. One might reasonably expect that technological progress will continue in the future as well. This thesis contributes to a better understanding of the economic implications of such progress and supports informed policy-making in a pursuit of a better organization of modern transportation.

An increase in both population size and household's prosperity has kept intensive and extensive margins of travel on a rise in the past.<sup>2</sup> As a result, transportation expenditures have never ceased to be an important part of household budgets<sup>3</sup>, and governments often fueled substantial public funds into transport infrastructure. Nevertheless, and despite the last century's progress, transportation still faces problems that are sometimes remarkably similar to the ones from one hundred years ago. Environmental nuisances due

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<sup>1</sup> Glaeser and Kohlhase (2004) document 90 percent decline of per ton-mile railroad shipment cost in the USA between 1890 and 2000. Hummels (2007) reports 92 percent decline of per ton-kilometer air shipping cost over the period from 1955 to 2004. Without accounting for quality change, a price of a basic Ford car and passenger rail travel in the USA have declined in real terms by about 50 percent between 1900 and 2000 (The Economist, 2000). During the last century fuel-efficiency improved by a factor of five (Lawyer, 2007). A maritime journey from London to New York lasted six days in 1910, while the same trip by an airplane took around seven hours in 2010 – that corresponds to a speed improvement of more than 95 percent.

<sup>2</sup> For example, according to Tarr (1996), in 1908 the total number of horses (probably the closest analogue to cars in those days) in New York was 150,000, while the total population was 4.7 millions. In 2008 there were more than 1.5 million cars in the city of 8.4 millions. Total road vehicles passenger-kilometers traveled in the USA more than tripled in the time period between 1960 and 2010, and both average vehicles-kilometers per household and average number of vehicle trips have increased (US Department of Transportation, 2014).

<sup>3</sup> The share of US household expenditure on transportation stays around 14 percent for several decades (US Department of Transportation, 2014).

to peculiarities of the animal-drawn transport have turned into concerns over air and noise pollution. Congestion has increased over the last decades<sup>4</sup> and traffic safety remains an issue. Privatization of transport facilities and regulation of private transport firms rarely fail to ignite public debate, as the outcomes of such policies are not always easy to anticipate, and typically benefit some and harm others. While engineers, urban planners and, among others, economists have contributed to an improved efficiency of transportation, the persistence of yet unresolved issues indicates the need for innovative ways to approach them.

This dissertation examines, from an economic viewpoint, a number of intriguing transport policy measures that became viable due to the recent development of information technologies which broadly include the Internet, wireless communications and powerful computing devices. The choice of policies analyzed in this thesis is in part guided by the aspiration to fill certain gaps in the research agenda that previous literature has indicated. One such policy measure is an out-of-office flexible work arrangement, also known as teleworking. It is often believed that teleworking can reduce the extent of travel between home and work locations, and thus decrease the negative external effects of travel, especially during rush hour. Chapter 2 develops a theoretical model that examines the effect of teleworking on morning traffic congestion, while chapter 5 empirically estimates the causal impact of information technologies that enable working from home on the employees' commuting distances.

Another policy tool that modern technology supports is the provision of traffic information to drivers. Better informed drivers might better succeed in avoiding bad traffic conditions in case less problematic alternatives are available. The welfare effects of private and public provisions of travel information and road infrastructure are investigated in chapter 4.

This thesis also looks at road pricing, which is among most economists' favorite measures to curb road traffic congestion. Increased availability of advanced technological solutions may facilitate the introduction of first-best road toll that might vary across many dimensions, e.g., time, vehicle type, and location. Chapter 3 proposes a theoretical framework suitable for the analysis of

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<sup>4</sup> Yearly hours delayed per auto commuter in large US urban areas have tripled in the period from 1980 to 2010 (Texas A&M Transportation Institute, 2014).

rush hour congestion, and policy measures that could tackle it, when location choices of individuals are affected by transport choices and vice versa.

Whether and under what conditions these technology-driven measures lead to socially desirable changes in travel behavior of individuals is the key question that the subsequent chapters will try to address. The main findings and policy implications are highlighted in the concluding chapter, which also mentions some promising topics for future research. The rest of the introduction briefly outlines the concepts of information technologies and road pricing in transportation, discusses the notion of congestion, and also gives an overview of the thesis and sets its scope.

## **1.2 Information technologies in transport**

### **1.2.1 Travel complementary**

Following Salomon (1986), one can broadly distinguish between travel complementary and travel substitute types of information technologies; the latter type is the focus of the next subsection. The former type refers to advanced travel information systems, satellite navigation and any other kind of information device or service that gives drivers a better idea about the situation on the roads. For example, traffic navigation systems can inform about road accidents, adverse weather conditions and other impediments on the way. Travel information could be historic, current and predictive, and might be available to everyone via interactive road signs and radio announcements, or to certain drivers only, for instance, via private electronic devices (Ben-Akiva et al., 1991). There are many real life implementations of travel information provision technologies, both proprietary and open source. At the risk of being obsolete in a short while, two examples of these are, respectively, Garmin real-time traffic information updates for subscribed users and the free-of-charge Waze smartphone application run by Google and integrated into Google Maps services. Information precision, reliability and cost vary greatly across information providers, which often use different technologies to gather and convey travel information.

Economists often consider information provision as a revelation of a particular realization of a stochastic state-of-the-world. An alternative approach would be to assume deterministic nature and imperfectly informed individuals,

as suggested in Footnote 6 by Arnott et al. (1996). Depending on the context, a realization may be expressed as a binary (e.g., open/closed bridge) or continuous measure (e.g., meters of visibility). In turn, less than perfect information about current, past or future state-of-the-world, may be presented as a distribution of potential realizations with probabilities associated with these realizations, e.g., 70 percent chance of snow on the road.

Starting from Stigler (1961), the value that an individual is willing to pay for additional information is broadly equal to the marginal benefit one derives from it minus marginal cost of information acquisition which involves not only monetary, but also effort and time costs. Researchers might define benefits of travel information in various ways, depending on the assumed initial knowledge of the drivers and whether information is about past or current realizations. For example, Emmerink et al. (1998a) adopt a utility-maximization approach under which value of travel information is equal to the difference of expected generalized travel costs incurred by traveling with and without information when all travel options, but not their costs, are known to travelers. Other studies, for instance, Arentze and Timmermans (2005), also include learning gains as a benefit of information, if not all travel possibilities are known to the driver a priori. Chorus (2014) notes that the acquisition of ex-post travel information about forgone travel alternatives might cause the feeling of regret, which a driver might want to avoid, even at the cost of giving up the knowledge about possibly better travel options. It seems that the choice of which benefit elements to include in the analysis is, at least partly, driven by the desire to keep the tractability and focus of a particular study, and most of these studies should be seen as complementing rather than opposing each other. This thesis refrains from considerations of non-rational behavior of individuals.

Empirical literature on travel behavior analyzes factors behind information acquisition and subsequent travel choice making and, in general, confirms the notion that travelers compare costs and benefits when making decisions whether to acquire information or not (e.g., Chorus et al., 2010). Through a learning process, which might be affected by both the qualities (in various dimensions) of information and the generalized travel costs, individuals adjust travel behavior (Mahmasanni et al., 2013). Empirical studies often rely on stated-preference survey to elicit the willingness to pay estimates (e.g., Molin and Timmermans, 2006). For a literature overview about information impacts on traveler behavior we refer to Balakrishna et al. (2013).

Many studies consider only the effect of information on the well-being of an informed individual, and do not consider equilibrium effects of information on all informed and uninformed drivers. These effects may be negative when individual travel costs depend on the travel behavior of other drivers, and are not optimally priced. The most prominent example of such a cost dependency is road congestion. Road congestion arises if a car hinders travel for the other vehicles, by inducing them to slow down or even, in case of a traffic jam, to stop for some time. Normally, drivers do not account for the fact that their presence on a road makes travel more difficult for others. This makes it a negative externality which is a well-known phenomenon also outside transportation, for example in an environmental setting in which a polluter does not bear the (full) cost of pollution.

Provision of traffic information under congestion might guide drivers away from congested roads, or might induce drivers to choose different modes of transportation or different times of travel. But information can also result in “concentration” of informed drivers in previously uncongested roads, which might lead to more traffic jams, as drivers tend to change their travel behavior in the same way (Arnott et al., 1991). Provision of traffic information, in case congestion is not internalized, may even be welfare reducing when the news about a high road capacity level brings a large inflow of additional drivers on the roads who are attracted by the lower generalized travel cost (Arnott et al., 1996). In line with this result, several studies show that the elasticity of travel demand is a key factor behind the usefulness of information (Emmerink et al., 1998a).

Strategic manipulation of information in order to reach the social optimum seems not sustainable in the medium or long run, if the social optimum is not aligned with the user-optimum, as drivers would adjust their behavior in response to information manipulation as soon as they find out about it. Similar to other second-best measures, such as road construction or promotion of public transit, travel information alone cannot fully solve the congestion problem (see, for other examples, the study of Duranton and Turner (2011) on road capacity expansion or Basso et al. (2011) on the introduction of dedicated bus lanes).

Besides the congestion externality, the industrial organization of the market for information provision might affect the social desirability of travel information as well (Zhang and Verhoef, 2006). Several papers, among others



Emmerink et al. (1998b), de Palma and Lindsey (1998), Yang (1999) and Fernandez et al. (2009), explicitly analyze the welfare effects of endogenous travel information provision and its pricing mechanics. Furthermore, Small and Verhoef (2007) point out that not only welfare-maximizing, but also profit-maximizing road operators have incentives to internalize congestion externality, as such internalization is efficient and allows private firm to appropriate an additional share of consumer surplus. An analysis of strategic interactions between public and private suppliers of road and information in case congestion is fully internalized (or not present) seems warranted and chapter 4 of this thesis contributes to the literature by developing a microeconomic model of such a market where demand for information is endogenous and both information and road prices are set strategically.

### 1.2.2 Travel substitution

While travel information provides a possibility to choose a travel option with lower generalized travel cost and thus eventually increases price-sensitive travel demand, substitute type of information technology might induce individuals to abstain from travel altogether. Internet shopping, video chatting, and working from home via the Internet render physical presence at a particular location, such as a shop, a friend's house, or the office unnecessary. Increasingly powerful portable computers, tablets and smartphones connected to Internet make virtual access easier and cheaper in comparison to costly, in monetary, time and effort terms, physical travel.

Since the word "telecommute" has been coined by Nilles in 1975, teleactivities have attracted much attention in the literature (see, e.g., Mokhtarian, 1990, 2003; de Graaff and Rietveld, 2007). Bailey and Kurland (2002) and Andreev et al. (2010) provide comprehensive overviews on the state of research on teleactivities. Teleactivities might, for example, facilitate a better work-life balance and a better job matching (through teleworking and online job search), and lower search time costs (via online shopping). Further social benefits can possibly be reaped from teleactivities in terms of reduced negative transport externalities such as pollution, traffic accidents and congestion, when teleactivities reduce travel.

Among all teleactivities, teleworking is probably the one that might alleviate congestion the most. This is true in particular for recurrent congestion, which arises when demand for road capacity is high relative to supply on a

recurrent basis. Notorious examples of such congestion are morning and evening rush hours, when road networks have to accommodate large flows of commuters within a relatively short period of time. In contrast to commuting, shopping or leisure trips usually have more scheduling flexibility and often take place outside rush hours. As the argument goes, individuals who work from home during the entire day might skip commute completely, while part-day teleworkers can avoid peak periods and travel to work outside rush hours. Chapter 2 analyzes the welfare effects of the endogenous part-day teleworking in the presence of congestion.

Empirical studies of teleworking so far have been mainly descriptive, especially concerning long-run effects, due to data unavailability. Despite our terminology, whether travel substitute technology actually reduces vehicle-kilometers traveled or increases them, is an empirical question, as additional activities might induce more travel. For instance, individuals might start to complement online shopping with trips to shops to see the products before the purchase. Nevertheless, Andreev et al. (2010) find that the majority of studies that consider teleworking suggests that it negatively correlates with total travel.

Lund and Mokhtarian (1994) note that in the medium and long run individuals might adjust their travel behavior in response to monetary and time gains that the adoption of teleactivities provides. One of the reasons why the total extent of travel might increase is due to the long-run spatial relocation of home and work locations that individuals (and firms) might undertake because of teleworking. Safirova (2002), Rhee (2008) and Glaeser (2008, p. 41) develop theoretical models that show that teleworkers might indeed choose to live further away from their work locations. However, reverse causality complicates an empirical estimation of this phenomenon, as it is not obvious whether employees who live far away choose to telework, or teleworking individuals choose to live further away. We attempt to uncover the causal effect of teleworking technologies on commuting distances empirically in chapter 5, by employing a difference-in-differences estimation procedure together with propensity score matching.

### 1.3 Road pricing

Another topic of this dissertation concerns the economics of road pricing. Toll roads or turnpikes have existed for many centuries, mainly as a source of

revenue for the ones who own a given transport artery (Levinson, 1998). Nowadays, road charges are seen not only as means for revenue extraction but also as a corrective mechanism for negative externalities, such as congestion, air or noise pollution, which the travelers impose on others. Arthur Pigou (1920) proposed a well-known tax that can be characterized as the first-best solution to the problem of negative externalities. The Pigovian tax yields a Pareto-optimal allocation of resources, by imposing on an individual a toll that will make her equate her marginal benefits with the marginal social cost of her actions. Most modern (micro) economic textbooks cover the topic of externality pricing in great detail (e.g., Mas-Colell et al., 1995).

While the Pigovian analysis provides a valuable insight into the problem of negative externalities, the dynamic nature of congestion, with an easily recognizable temporal pattern of waiting time that increases at the beginning of the rush hour and then subsequently decreases, led transportation economists to develop an alternative analytical framework. William S. Vickrey, the Nobel Prize laureate, formulated in 1969 a novel fundamental equilibrating principle behind behavior in traffic jams, and in many other queues: the trade-off that individuals make between costs of arriving at an inconvenient time, versus the cost of waiting in the queue. That is, a driver who arrives early in the morning faces low or no waiting times on the road, but incurs higher costs of being at work earlier than she would otherwise prefer, while a driver who arrives exactly at the preferred arrival time has to bear costs of a relatively long wait in a queue. The model, known as the bottleneck model, further extended by, among others, Arnott et al. (1990, 1991, 1993), introduces the concept of a dynamic equilibrium, which implies that all commuters attain the same level of utility with varying shares of travel delay and schedule delay costs, and no driver can get a higher utility by unilaterally changing the departure time.

An important feature of the bottleneck model is that the time-dependent socially optimal road toll eliminates waiting time completely, and it leads to a Pareto improvement if the revenues from road pricing are returned back to the drivers. Despite the broad consensus among economists on the positive role that road tolls might play to fight traffic congestion, practical implementation of congestion tolls is still limited to a few cities (among them are London, Singapore, Stockholm), and some US highways with dedicated toll lanes. The literature emphasizes a low political and social acceptability, often on the ground of the resulting income redistribution that leaves most travelers worse-

off and possibly favors some well-off drivers (Button, 2004). Solutions based on information technologies are one of several proposed alternatives to pricing. Teleworking is one of them, and this thesis analyzes the welfare effect of teleworking on road congestion in chapter 2.

There are several other economic models of traffic congestions, aside of the bottleneck model, which explicitly study departure time decision of an individual when this decision affects generalized travel costs of other drivers. The most distinct feature of these models as compared to the bottleneck model is a non-monotonic relationship between absorbing capacity of the traffic system and the overall number of cars in it. Road capacity in the bottleneck model increases with the number of cars until a certain value, above which the capacity stays constant. In other models, such as bathtub model of congestion (e.g., Arnott, 2013; Fosgerau and Small, 2013; Fosgerau, 2014), the capacity might decrease with the number of cars in the system. In its limit, this capacity might even diminish to zero, implying a gridlock and a full stop of traffic. Recent empirical studies show evidences of such relationship at both microscopic and urban levels (Geroliminis and Daganzo, 2008; Daganzo et al., 2011). One of the reasons why chapters 2 and 3 are cast in the framework of the bottleneck model is its analytical convenience that allows closed-form solutions. More importantly, analysis under more elaborated road capacity (supply) function does not change the main behavioral responds of drivers to congestion and road pricing, as long as the latter reduces duration of travel, which is the case both under bottleneck and alternative models specifications. However, a more realistic treatment of congestion dynamics might yield quantitatively more plausible estimates and thus future studies would benefit from incorporating such aspects in the models.

Changes in travel cost may affect behavior of travelers also on other markets, such as labor participation or residential location. A standard result of introducing Pigovian road pricing in a city is the diminishing geographical extent of a city (Wheaton, 1998), while Arnott (1998) found an absence of a direct link between Vickrey pricing and urban structure. In contrast, chapter 3 notes that first-best road pricing results in an increase of time spent at home, which in turn might induce stronger demand for housing. Chapter 3 shows that Vickrey's road toll may thus lead to city expansion.

## 1.4 Overview of the thesis

This dissertation contains six chapters, including Introduction, four research chapters and Conclusions, each presented in a self-contained form to allow for independent reading. Chapters 2 – 4 develop theoretical models, while chapter 5 is an empirical exercise. A common reference list follows the Conclusions.

Chapters 2 and 3 consider the morning commute, which involves passing through a congested road bottleneck and, from a methodological point of view, both are based on the dynamic bottleneck model due to Vickrey (1969).

Chapter 2 analyzes the welfare effects of a teleworking-enabling technology (such as access to databases via the Internet and videoconferencing), which allows employees to work from home. We model the welfare impact of such a technology as an increase in utility of being at home in the morning. We keep the structure of the bottleneck model intact by assuming that after a certain time in the morning, e.g., 9 am, the utility of being at work becomes larger than that of being at home, even for teleworkers, thus all employees retain an incentive to commute. In this chapter we derive the marginal willingness to pay for the technology and show that equipping an additional driver with the teleworking-enabling technology changes her commuting pattern and, due to congestion externalities, affects travel costs of all drivers. We show that in the absence of optimal congestion pricing, even costless teleworking might be marginally welfare reducing, after the second-best optimal penetration level is exceeded, as an equipped driver imposes a higher travel externality on other equipped drivers than unequipped drivers do. We also study market organization, and find that private monopolistic supply of the technology might yield a higher social welfare than perfectly competitive supply.

Chapter 3 investigates the long-run effect of first-best dynamic congestion pricing on the spatial behavior of commuters in the context of the monocentric city model. This is a popular urban model where residential location choices of individuals, house sizes, and rents are endogenous. We consider a city with a Vickrey traffic bottleneck, which is located at the entrance of the central business district where everyone has to commute to. Effectively, we impose both dynamic and spatial equilibrium conditions that insure that no individual can improve her welfare by unilaterally changing residential location, house size, or departure time from home. We show that first-best time-dependent

road pricing induces individuals to spend more time at home by postponing the trip to work, as queuing is eliminated. That induces city residents to obtain larger houses, as the utility derived from housing space increases in the amount of time spent at home. It then follows that road pricing causes urban sprawl. This result is opposite to the typical results of urban models with static congestion, which predict cities to become denser with road pricing.

In chapter 4 we turn to the welfare analysis of various markets under alternative ownership regimes in which a road supplier and a provider of traffic information strategically interact to accommodate the demand from road users for both road capacity and traffic information. We follow Emmerink et al., (1998b) and explicitly derive the demand for information from an exogenously given demand for travel, and stochastic travel costs. Using a game-theoretical analysis of suppliers' pricing strategies, we assess the social welfare effects of traffic information provided under various ownership regimes. The results show that the distortive welfare effect of monopolistic information pricing appears relatively small. Collusion of the road operator and information provider yields higher social welfare than independent pricing by two firms. The intuition behind this result resembles that behind the welfare effects of double marginalization, but is not exactly the same, as traffic information is not strictly (only voluntarily) complementary to road use.

In chapter 5 we infer the causal impact of teleworking technologies on commuting distances in the Netherlands. Based on Labor Force Survey data for 1996 and 2010 we estimate, combining difference-in-differences and propensity score matching approaches, the change in commuting distances for employees in professions in which teleworking is feasible and widespread. Our identifying key assumption is that the change over time in commuting distances between the teleworking and non-teleworking professions is entirely due to differences in technology. The main advantage of our method is that it explicitly allows for endogenous sorting (of jobs) within the profession.

Finally, in the concluding chapter we offer some closing remarks, formulate some policy recommendations and suggest a few promising lines of research for the further analysis of economic effects of emerging technologies on travel.



## 2 Teleworking and congestion: A dynamic bottleneck analysis

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### 2.1 Introduction<sup>5</sup>

Road congestion is a challenging and persisting problem. Various policy measures have been proposed to tackle congestion, including investment in transport infrastructure and public transit, provision of traffic information to drivers, city zoning, road pricing, parking policies and flexible working hours. Since Pigou (1920), most economists agree that marginal cost pricing of roads offers the first-best solution to congestion problems; see, for example, the exposition in Small and Verhoef (2007). However, optimal tolling seems technically hard to implement in practice; and in part due to its redistributive effect, pricing suffers from low political acceptability that further hinders a wide implementation. There are only a few cities, the best-known being Singapore, Stockholm, London, and Milan with road pricing schemes, usually in the form of a fixed or step cordon toll. The limited feasibility of the first-best policy motivates an ongoing search for alternatives.

Teleworking is one such possible alternative. It refers to out-of-office work arrangements, usually from home and sometimes with flexible time schedules. Whole-day teleworking allows an individual to avoid commuting between the home and the workplace altogether, while part-day teleworking could make it easier to circumvent congestion by commuting during off-peak hours. Progress in information and telecommunication technologies (hereafter, ICT), such as the availability of the remote access to secured databases, cloud computing, networks and a general advance of Internet technologies, expands both the intensive and the extensive margin of teleworking use. Moreover, governments stimulate teleworking use. For instance, in the USA, the Telework Enhancement Act of 2010 promotes teleworking among public servants. Given the range of potential benefits on labor productivity, work-life balance, job matching, and

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<sup>5</sup> This chapter is in a revise and resubmit stage in a peer-reviewed journal. An earlier version of this study is printed in the Tinbergen Discussion Paper series (Gubins and Verhoef, 2011).



given expected future technological progress, one may expect teleworking to be of increasing relevance in the future.<sup>6</sup>

Against this background, this chapter will investigate the effects of part-day (morning) teleworking on congestion, from the economic perspective. Part-day teleworking is an empirically relevant phenomenon; for example, one UK survey shows that in 2007 part-day teleworking rates of 17.2 and 9.8 respectively (Haddad et al., 2009). In the context of this chapter, one might think of the employees performing some work tasks from home in the morning, and then coming to an office for the rest of the workday.

Studies that do model the impacts of teleworking on travel typically focus on the spatial dimension, notably to capture the long-term effects of whole-day teleworking on residential choice within a city; see, among others, Safirova (2002), Rhee (2008) and a short subsection on job decentralization in Glaeser (2008, p. 41). But time-of-day adjustments may also be relevant, especially for part-day teleworking. To effectively incorporate this temporal aspect of part-day teleworking, we apply Vickrey's (1969) dynamic bottleneck model, a work-horse model in transportation economics, in which the drivers' scheduling decisions are endogenous.

We model the behavioral impacts of teleworking by assuming that access to the teleworking-enabling ICT raises the utility that an individual derives from being at home at any given point in time. We therefore define a teleworking individual as a person who is equipped with a technology that allows her to perform various work tasks from home. An equipped individual values time spent at home higher than an unequipped one, and, as we show later, has an incentive to therefore postpone the arrival time at work. The choice of whether to be equipped is determined within the model; thus our model may produce endogenous heterogeneity of drivers when not everybody chooses to become equipped. We derive an inverse demand for the teleworking technology, and show that the marginal willingness to pay depends negatively on the number of teleworking people, due to the relatively large congestion externality equipped drivers impose on one another. We show that even costless technology might be marginally welfare reducing after teleworking

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<sup>6</sup> Increase of the teleworking incidence rate over time has occurred in the past. According to the Eurofound surveys (2005, 2010), an employees' self-reported EU average incidence rates of teleworking for at least one-quarter of their time were 4 and 7 percents in, respectively, 2000 and 2005, with large variation across countries, industries and days of the week.

reaches a certain optimal penetration level. We also study private market provision of the teleworking technology, both under perfect competition and monopoly, and define conditions when the social welfare is found to be higher under monopoly.

Our study fits in a wider literature that considers the potential impacts of ICT on congestion and social welfare. However, most of this literature focuses on the provision of traffic information to drivers; see for example, Arnott et al. (1996), de Palma and Lindsey (1998), and Emmerink et al. (1998a, 1998b). These studies consistently show that under an unpriced congestion externality, the marginal effect of information might sometimes be welfare decreasing. To the best of our knowledge, our study is the first to show this in the context of teleworking. Given the popularity of ICT-based solutions to traffic congestion, these results are important for practical policy making.

The chapter is organized as follows. Section 2.2 introduces Vickrey's dynamic bottleneck model, and teleworking within that framework. Section 2.3 derives the marginal willingness to pay for and social benefits of teleworking. Section 2.4 considers private provision of the teleworking technology in markets of perfect competition and monopoly. We evaluate the relative efficiency of market outcomes, compared to the social optimum. Section 2.5 considers the impact of teleworking on travel in case first-best road tolling already addresses the congestion externality. Section 2.6 summarizes the chapter, highlights the main findings, and concludes with a list of possible extensions.

## **2.2 Teleworking within Vickrey's dynamic bottleneck model**

### **2.2.1 Basic model**

Our analysis is cast in the framework of Vickrey's (1969) dynamic bottleneck model, which provides a stylized description of traffic congestion at a single traffic bottleneck. The model builds upon the observation that traffic congestion in reality is a dynamic phenomenon; with waiting times and queues first increasing over time during the rush hour, and subsequently declining. Vickrey's model explicitly considers the decisions of drivers to start travel at certain moments in time, and applies a dynamic equilibrium condition in which no driver can be better off by unilaterally changing the departure time.

In its simplest form the dynamic bottleneck model considers a morning period during which  $\bar{N}$  homogeneous atomistic car drivers decide on the time of departure from a single origin (“home”) to a single destination (“workplace”). Drivers have the same preferred arrival time at work,  $t^*$ , a deviation from which causes a driver to incur a schedule delay cost. There is a road bottleneck in between home and work, possibly a bridge or a tunnel, with a capacity  $s$ . Thus, a “first-in first-out” traffic jam starts to build up after the flow of drivers arriving to the bottleneck has first exceeded its capacity. Each minute of spending time in a traffic jam results in a travel delay cost for a driver. The free-flow travel time is set to zero, without loss of generality in this context, implying that without a queue drivers depart from home, pass the bottleneck and arrive at work all at the same moment.

The dynamic bottleneck model highlights an important equilibrating mechanism affecting behavior in a traffic jam: the trade-off that drivers make between schedule delay costs of arriving at an inconvenient time, versus the travel delay cost of waiting in the queue. This stylized description of traffic congestion offers a framework for studying dynamic departure time decisions, and the dynamic evolution of traffic conditions over the rush hour period, within one analytical model that lends itself to closed-form solutions of optima and equilibria (e.g., Arnott et al., 1993).

The standard dynamic bottleneck model uses a linear cost function setup, in which there is a time-invariant value of travel time ( $\alpha$ ), a constant unit shadow price of schedule delay for arriving early ( $\beta$ ), and one of schedule delay for arriving late ( $\gamma$ ). This scheduling setup is attributed to Vickrey (1969) and Small (1982), and now extensively used in the transportation economics literature. Vickrey (1973), and later Tseng and Verhoef (2008), considered a somewhat more general specification of scheduling behavior and utility, which explicitly describes the underlying pattern of activities in terms of time-variant utilities of being in various locations. This approach is useful for our purposes, as it allows us to incorporate the impact of teleworking technology in the bottleneck model in a structured way. In this approach, a driver derives utility from being either at home ( $H(t)$  per unit of time), at work ( $W(t)$  per unit of time), or in a vehicle ( $V(t)$ , standardized at zero for convenience).<sup>7</sup> While many

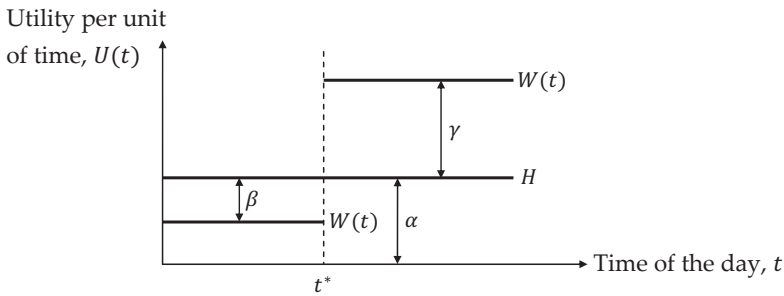
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<sup>7</sup> Strictly speaking,  $H$ ,  $W$  and  $V$  are Marshallian surpluses, which are the ratios of marginal utility of time spent at respectively, home, work and in a vehicle, over marginal utility of income. For brevity we refer to them as utilities.

functional utility specifications for  $H(t)$  and  $W(t)$  are possible, Tseng and Verhoef (2008) show that only one particular specification is equivalent to the standard linear scheduling setup. In this specification  $H(t)$  is equal to some constant ( $H$  henceforth) throughout the period considered, while  $W(t)$  is piecewise constant with an upward jump at  $t^*$ , and  $W(t) = W_E < H$  before  $t^*$  and  $W(t) = W_L > H$  after  $t^*$ . The equivalence with the conventional linear function stems from the fact that the opportunity cost of being at work before  $t^*$  is, then,  $H - W_E = \beta$ ; the opportunity cost of not being at work after  $t^*$  is  $W_L - H = \gamma$ ; and the opportunity cost of being in a vehicle is  $H - V = \alpha$ . The usual assumption that  $\alpha > \beta$  translates into  $V(t) < W(t)$ , and reflects that a driver prefers to enter the workplace above staying in the car after having passed the bottleneck. We plot this utility structure in Figure 2.1.

We use the above linear utility specification, primarily to stay as close as possible to the conventional linear scheduling setup which assumes constancy of  $\alpha$ ,  $\beta$  and  $\gamma$ ; and which has been applied in most of the bottleneck model literature. We see no immediate reasons why insights on the desirability of different market structures for the supply of teleworking technology would depend critically on this specific functional form.

**Figure 2.1.** Utility structure and opportunity costs for a driver in the conventional representation of Vickrey's dynamic bottleneck model



Based on Tseng and Verhoef (2008), Figure 2.

With inelastic demand, the single margin of behavior in the bottleneck model is the arrival time at work,  $t$ , which a driver sets to maximize utility over the course of the morning. We define the morning period such that it starts for

every driver at the common time  $t_S$  and finishes at  $t_F$  (chosen such that the interval is wide enough to cover the entire congestion period or peak). An individual's utility level is then equal to an "ideal" utility level  $\Gamma$ , which she would reach over the course of the morning, had she both departed and arrived at the preferred arrival time  $t^*$ , minus the generalized travel cost that she actually incurs. The latter consists of travel delay and schedule delay costs, and will be denoted  $P(t)$ . A driver incurs schedule delay cost when the time of her arrival at work is not  $t^*$ . Each minute of arriving at work either early or late has a value of, respectively,  $\beta$  and  $\gamma$ . In turn, each minute of travel delay,  $T(t)$ , has a value of time  $\alpha$ .

Thus, the utility level of a driver arriving at work at time  $t$  is:

$$(1) \quad U(t) = \Gamma - P(t) \\ = \alpha(t^* - t_S) + (\alpha + \gamma)(t_F - t^*) - \alpha T(t) - \begin{cases} \beta(t^* - t) & | t \leq t^* \\ \gamma(t - t^*) & | t > t^* \end{cases}$$

Note that the first two terms are constants, and the final two (time-dependent) terms correspond to the conventional generalized cost of travel.

To determine the dynamic equilibrium (see also Vickrey, 1969; and Arnott et al., 1993), first observe that in accordance to the dynamic equilibrium the utility levels of all (homogeneous) drivers must be equal; i.e., no one is able to adjust her arrival time and consequently gain in utility. The very first driver arrives at work at time  $t_q$  and faces no travel delay costs, as she freely passes the bottleneck. But she incurs schedule delay costs from being early at work; thus, her generalized cost is  $\beta(t^* - t_q)$ . Likewise, the very last driver who arrives at time  $t_{q'}$  incurs the cost of arriving late at work but again faces no travel delay; the generalized travel cost is then  $\gamma(t_{q'} - t^*)$ . Because the ideal utility level  $\Gamma$  is identical across homogeneous drivers, the equilibrium condition implies equality of generalized travel costs. Given that the duration of the peak period is  $\frac{\bar{N}}{s} = (t_{q'} - t_q)$ , the peak period starts and ends at:

$$(2) \quad t_q = t^* - \frac{\gamma}{\beta + \gamma} \frac{\bar{N}}{s}$$

$$(3) \quad t_{q'} = t^* + \frac{\beta}{\beta + \gamma} \frac{\bar{N}}{s}$$

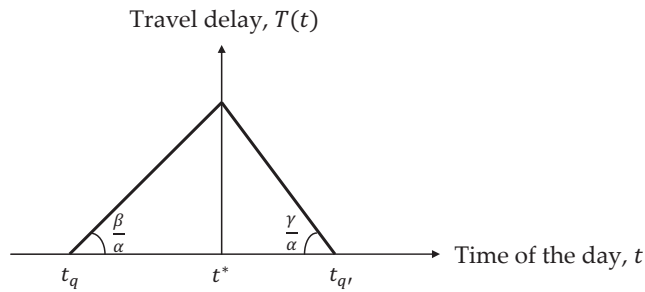
Each driver therefore faces generalized travel costs equal to:

$$(4) \quad P(t) = \frac{\beta\gamma}{\beta + \gamma} \frac{\bar{N}}{s}$$

The driver who arrives at work at time  $t^*$  only incurs travel delay cost  $\alpha T(t^*)$ . In equilibrium, she has the same generalized travel cost as the first driver; hence her waiting time in a traffic jam is  $T(t^*) = \frac{\beta\gamma}{\beta + \gamma} \frac{\bar{N}}{s} \frac{1}{\alpha}$ .

In equilibrium, when generalized costs are identical across drivers, for those who arrive before  $t^*$  each additional one minute arrived closer to  $t^*$  decreases the schedule delay cost by  $\beta$ , but must increase travel delay by  $\frac{\beta}{\alpha}$  to keep generalized cost constant over time. In the same fashion, for arrivals later than  $t^*$  the travel delay decreases with  $\frac{\gamma}{\alpha}$  by arrival time to keep generalized cost constant. Figure 2.2 shows the equilibrium combinations of arrival times and travel delays. The slopes of the triangle naturally depend on the parameters  $\alpha$ ,  $\beta$ ,  $\gamma$ ; while the width depends on  $\frac{\bar{N}}{s}$ , which determines the duration of the peak (the time interval between  $t_q$  and  $t_{q'}$ ). As the generalized costs are constant over time, one may interpret the graph as an isocost function. As there are no arrival times with a generalized cost level below the equilibrium level, and given that vehicles are treated as a continuum, the equilibrium in Vickrey's dynamic bottleneck model is a Nash equilibrium.

**Figure 2.2.** Equilibrium isocost function with homogeneous drivers



### 2.2.2 Introduction of teleworking technology

The framework shown in Figure 2.1 helps us to make a structured and well-motivated assumption on how the availability of teleworking technology would affect the value-of-time components  $\alpha$ ,  $\beta$  and  $\gamma$ . Maintaining a piecewise

constant utility structure, and assuming that the technology would affect the utility of being at home (not of being at work or in the vehicle), the natural assumption to make is that it shifts  $H$  upwards; and does so by some constant as we want to maintain the qualitative pattern displayed in Figure 2.1. This means that, in terms of the conventional scheduling formulation, adaptation of teleworking technology will lead to equally large increases in  $\alpha$  and  $\beta$ , and a decrease in  $\gamma$  that is equally large in absolute size. Intuitively, an individual equipped with the teleworking technology would put a higher value on time spent at home before  $t^*$ , as being at home results in higher utility due to the possibility of teleworking. At the same time, for an equipped driver, who arrives at work after  $t^*$ , a trip does not cause as much cost as for an unequipped one, as the teleworker may reduce the disutility of a late arrival at work by working from home. And the conventional value of travel time  $\alpha$  increases because the opportunity cost of not being at home increases.

A constant shift in  $H$  due to teleworking technology implies that an equipped driver starts gaining higher utility from being at home right after the beginning of the morning, at  $t_s$ . That might represent that an equipped driver works during the entire morning, or, alternatively, that due to the availability of technology, an individual is able to reschedule other activities (not modeled explicitly) at home in such a way that the utility derived from being at home rises.

Of course, other assumptions could have been made on how teleworking would affect the utility function. We believe our assumption captures the most relevant aspect of the issue, in the simplest possible utility specification. Specifically, only with a constant upward shift of  $H$  would the individual, both before and after being equipped, have a utility function that can be characterized by the three conventional constant shadow prices  $\alpha$ ,  $\beta$  and  $\gamma$ .

We thus assume the technology raises the unit value of staying at home by a constant  $\Delta$ , for which we assume  $\Delta < \gamma$ . The latter inequality assures that also those drivers who are equipped with the teleworking technology still find it worthwhile to be at work at times  $t \geq t^*$ . Note from Figure 2.1 that our specification leaves the preferred arrival time  $t^*$  unchanged. This is in fact a welcome feature, because it secures that any predicted shift of the peak period that results from adaptation of technology by drivers, which we will indeed find in our model, can be ascribed solely to the impact of changes in  $H$ ,  $\alpha$ ,  $\beta$  and  $\gamma$ ; and not to a change of  $t^*$ .

## 2.3 Marginal willingness to pay for and externalities of teleworking technology

### 2.3.1 Marginal willingness to pay for teleworking technology

In this section we derive the marginal willingness to pay for acquiring the teleworking technology (*MWTP*). We will show that this willingness to pay depends on the aggregate level of technology penetration: if more drivers are equipped with the technology, an individual driver is willing to pay less for it. The intuition is that the equipped drivers tend to postpone their departure times to be “at the end of the peak” to gain most benefit from teleworking, but the rising number of the equipped drivers makes the end of the peak increasingly late, and this diminishes teleworking benefits and therewith marginal willingness to pay for it. Later we capture this result in Proposition 1, after having established Lemmas 1 and 2 first below.

The marginal willingness to pay for the teleworking technology is the difference between the utility that a driver reaches over the course of the morning when being equipped with the technology,  $U_e$ , minus the utility when being unequipped,  $U_u$ . As follows from Equation (1), changes in opportunity costs  $\alpha$ ,  $\beta$  and  $\gamma$ , affect an individual's utility  $U_{e,u}$  via a change in the ideal utility,  $\Gamma_{e,u}$ , and in the generalized travel costs that one incurs,  $P_{e,u}$ , where subscripts  $e$  and  $u$  denote, respectively, equipped and unequipped drivers:

$$(5) \quad MWTP = U_e - U_u = (\Gamma_e - P_e(t)) - (\Gamma_u - P_u(t))$$

The derivation of the ideal utility values  $\Gamma_e$  and  $\Gamma_u$  is straightforward. A driver equipped with teleworking technology has a higher ideal utility than an unequipped driver, because between  $t_S$  and  $t^*$ , a higher utility of being at home is enjoyed.<sup>8</sup> This increase in ideal utility is, of course, identical for all teleworkers, and does not depend on one's arrival time at work.

The derivation of equilibrium cost values  $P_e(t)$  and  $P_u(t)$  is more involved. Both equipped and unequipped drivers choose their arrival time at work  $t$  to minimize generalized travel costs. With different opportunity costs, the slopes of isocost functions as shown in Figure 2.2 may differ between drivers. Therefore, a driver who adopts the technology may have an incentive to change

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<sup>8</sup> The difference in ideal utility levels of equipped drivers  $\Gamma_e$  and unequipped ones  $\Gamma_u$  is  $\Gamma_e - \Gamma_u = \Delta(t^* - t_S) > 0$  whenever  $t^* > t_S$  and  $\Delta > 0$ , as we assume.



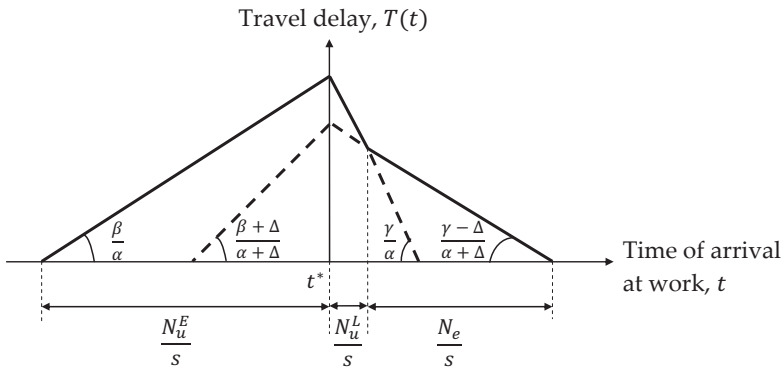
the arrival time at work, in order to minimize generalized travel costs under the new time values.

Dynamic equilibrium requires that for both groups of travelers, if both are greater than zero in size, the generalized travel costs are equal at moments when arrivals occur, and not lower at other times. We will see shortly that this will involve temporal separation of travelers when both types exist.

To see why this occurs, first note that the upper envelope of the groups' equilibrium isocost functions corresponds to the equilibrium pattern of travel delays. Let  $N_e$  be the number of equipped drivers, and  $N_u^L$  and  $N_u^E$  the numbers of unequipped drivers who arrive at work, respectively, after ("Late") and before ("Early")  $t^*$ . For a fixed overall number of drivers,  $\bar{N}$ , the duration of the peak period will be  $\frac{\bar{N}}{s} = \frac{N_e}{s} + \frac{N_u^L}{s} + \frac{N_u^E}{s}$ . The timing of the beginning of the peak, however, is endogenous.

To determine the equilibrium level of generalized cost, we have to distinguish between two cases, one with relatively low numbers of equipped drivers ( $0 \leq N_e \leq N_e^\#$ ), and another with relatively high numbers ( $N_e^\# < N_e \leq \bar{N}$ ), where  $N_e^\#$  is defined later. With low numbers, equipped drivers will arrive only after  $t^*$ . Figure 2.3 illustrates this type of equilibrium, and shows the equilibrium isocost functions for both types of drivers. The isocost lines of unequipped drivers have slopes  $\frac{\beta}{\alpha}$  and  $-\frac{\gamma}{\alpha}$ ; those of equipped drivers have slopes  $\frac{\beta+\Delta}{\alpha+\Delta}$  and  $-\frac{\gamma-\Delta}{\alpha+\Delta}$ . The slopes for equipped drivers are, therefore, steeper for early arrivals and flatter for late ones.

**Figure 2.3.** Isocost functions of the heterogeneous drivers, if equipped drivers arrive at work late



It is very easy to prove that the first single (atomistic) driver who gets equipped prefers to be the last traveler passing the bottleneck. Given the equilibrium isocost line for unequipped drivers, which gives the equilibrium pattern of travel times for this group, the last arrival time brings the single equipped driver at the lowest achievable isocost line. This driver spends the peak period at home, benefits from teleworking, and then travels to work, incurring generalized travel costs of  $\frac{\beta(\gamma-\Delta)\bar{N}}{\beta+\gamma} \frac{1}{s}$ . As more drivers become equipped, their equilibrium isocost function will shift upwards to accommodate the increasing number  $N_e$ . At the same time, the equilibrium isocost of the unequipped group moves downward, as there is decreasing demand for early arrivals.

The different slopes of isocost lines in Figure 2.3 thus induce a temporal separation of travelers, where equipped drivers arrive later than unequipped ones. We summarize this result in Lemmas 1 and 2.

**Lemma 1.** The generalized travel costs for unequipped drivers  $P_u$  is decreasing when the share of equipped drivers  $N_e$  rises, i.e.,  $\frac{\partial P_u}{\partial N_e} < 0$ .

**Proof.** See Appendix.

The proof is straightforward; it entails deriving the duration of the interval where unequipped drivers arrive after  $t^*$  ( $\frac{N_u^L}{s}$ ) and the duration of the peak before  $t^*$  ( $\frac{N_u^E}{s}$ ). The former is non-negative if  $N_e$  is below the level that defines the threshold value  $N_e^\#$ :

$$(6) \quad N_e^\# = \frac{\beta(\alpha + \Delta)}{\beta(\alpha + \Delta) + \alpha(\gamma - \Delta)} \bar{N}$$

Lemma 1 implies that equipped drivers in some sense impose a positive external effect on unequipped drivers. More precisely, they impose a smaller external cost on unequipped drivers than unequipped drivers do themselves. The underlying reason is that the groups have different preferences for arrival time adjustments, where equipped drivers have a less strong demand for early arrivals. Lemma 1 is in line with a result of Lindsey (2004) who shows that drivers face lower trip cost when they travel with drivers unlike themselves than with an equal number of drivers like themselves.

**Lemma 2.** The generalized travel costs for equipped drivers  $P_e$  is increasing when the share of equipped drivers  $N_e$  rises, i.e.,  $\frac{\partial P_e}{\partial N_e} > 0$ .

**Proof.** See Appendix.

Lemma 2 implies that equipped drivers impose a negative marginal externality on their own group, that exceeds the negative externality that unequipped drivers impose on equipped drivers. Using results on generalized cost levels derived for Lemmas 1 and 2, we can find an expression for equation (5) which immediately leads to Proposition 1.

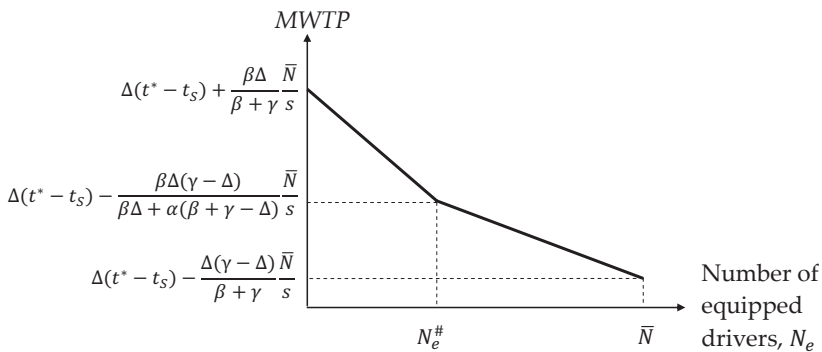
**Proposition 1.** *MWTP* is negatively related to the number of equipped drivers  $N_e$ , so if more drivers are equipped, an additional individual driver is willing to pay less for teleworking technology, i.e.,  $\frac{\partial MWTP}{\partial N_e} < 0$ .

**Proof.** See Appendix.

That *MWTP* decreases with the rise of  $N_e$  is true for both the marginal unequipped driver who becomes equipped, and also for the already equipped drivers, as these will have the same benefits of remaining equipped as the marginal equipped driver has. Hence, the total benefits for the equipped drivers collectively is  $MWTP \cdot N_e$ .

The slope of *MWTP* in the range  $N_e^\# < N_e \leq \bar{N}$ , is flatter than in the range  $0 \leq N_e \leq N_e^\#$ , resulting in a kink in *MWTP* function at  $N_e^\#$ . The reason for the kink is the difference in externalities imposed by early versus late equipped drivers. Figure 2.4 illustrates the *MWTP* as a function of  $N_e$  (see derivations in

**Figure 2.4.** Marginal willingness to pay for teleworking technology



the proof of Proposition 1 in Appendix). Although the *MWTP* is declining, also the very last driver to become equipped has a positive willingness to pay, as we set the start of the day  $t_s$  before the first driver arrives at work when teleworking possibility is not available (i.e.,  $t^* - t_s \geq \frac{\gamma}{\beta + \gamma} \frac{\bar{N}}{s}$ ). Under this constraint, the *MWTP* value at  $\bar{N}$ , as shown in Figure 2.4, is positive. A positive *MWTP* also for the last driver to become equipped is consistent with the notion that even when not changing departure time, this driver has benefited at a rate  $\Delta$  over the time spent at home between the start of the day and the moment of departing.

### 2.3.2 Marginal social benefit function

All drivers' generalized travel costs change when an additional unequipped driver becomes equipped. More precisely, with each additional driver becoming equipped, the already equipped drivers will incur higher costs, while unequipped drivers' costs decrease. Changes in costs for other drivers are external to the driver who becomes equipped. The (private) marginal willingness to pay function therefore does not correspond to the marginal social benefit function, as the latter includes the externalities.

To calculate the socially optimal level of teleworking, we derive the marginal social benefit function of teleworking technology (*MSB*). With zero marginal cost, the adaptation of the technology by an additional driver is socially desirable as long as *MSB* is non-negative; otherwise the number of teleworkers is socially excessive.

To determine the *MSB*, we distinguish between three types of drivers: the single (atomistic) driver who becomes equipped, the drivers already equipped ( $N_e$ ), and those unequipped ( $\bar{N} - N_e$ ). *MSB* is then equal to the sum of marginal willingness to pay (*MWTP*) of the driver who is becoming equipped, minus the marginal external costs for all equipped drivers, plus the marginal external benefits<sup>9</sup> to all unequipped drivers. The marginal external benefits to all unequipped drivers is the derivative of their generalized travel costs with respect to number of equipped drivers, multiplied by the number of unequipped drivers:

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<sup>9</sup> For brevity we refer to the decrease in marginal external cost for the unequipped driver as if it was a marginal external benefit.

$$(7) \quad MSB_u = -\frac{\partial P_u}{\partial N_e}(\bar{N} - N_e)$$

And similarly for equipped drivers:

$$(8) \quad MSB_e = -\frac{\partial P_e}{\partial N_e}N_e$$

One can also determine the  $MSB$  by taking the derivative of the total generalized travel costs of all drivers jointly with respect to the number of equipped drivers.  $MSB$  is then minus the resulting derivative plus the increase in ideal utility for a single driver who is getting equipped. It has been verified that the two approaches lead to the same result.

The marginal social benefit function is then the sum of  $MWTP$ ,  $MSB_u$  and  $MSB_e$ . We define  $MSB$  separately for both relevant ranges, of “low” and “high” number of equipped drivers. The slopes and intercepts of  $MSB$  over those two ranges differ, and overall  $MSB$  is discontinuous at  $N_e^\#$ . This discontinuity stems from the differences in external effects that drivers impose upon one another in early arrivals compared to late ones. Comparing  $MSB$  and  $MWTP$  we can next establish Proposition 2.

**Proposition 2.** The slope of the  $MSB$  function is twice as steep as the slope of the  $MWTP$ .

**Proof.** See Appendix.

The equilibrium level of  $N_e$  and its implication for the welfare of course depends on both the demand side for the technology, which we have just covered above, and on the supply side, which is the focus of the next section.

## 2.4 Supply of teleworking technology

### 2.4.1 Perfect competition

In this section we examine the pricing strategies of private (profit maximizing) and public (welfare maximizing) firms that could supply the teleworking technology to drivers. In particular, we are interested in the relative efficiency of private market outcomes, compared to the social optimum. The profit maximizing price is, for a given market structure, determined by the marginal willingness to pay through its impact on marginal revenue on the one hand,

and marginal costs on the other. At the same time, to reach the social optimum, a public provider should set a price that assures the equality of marginal social costs and marginal social benefits.

We assume that the marginal (social) cost of technology provision is zero. Besides simplifying the analysis, this assumption strengthens our finding that unrestricted supply of the teleworking technology might be marginally socially detrimental. The essential outcomes are not likely to change with the introduction of positive marginal costs. First, we will consider a market with perfect competition, where congestion is the single market friction. Then we introduce another market friction in combination to congestion: the existence of market power by a monopolist.

Under perfect competition the price is equal to zero marginal cost, so that in equilibrium all drivers are equipped with teleworking technology, i.e.,  $N_e^{PC} = \bar{N}$ . The reason is that the  $MWTP$ , following the discussion in the previous section, is always positive (see Figure 2.4). The total social benefits under perfect competition ( $TSB^{PC}$ ) is then the integral of marginal social benefits in both low ( $MSB_L$ ) and high ( $MSB_H$ ) ranges of technology adoption:

$$(9) \quad TSB^{PC} = \int_0^{N_e^\#} MSB_L dN_e + \int_{N_e^\#}^{\bar{N}} MSB_H dN_e$$

In contrast, a public firm sets the price and corresponding level of technology penetration,  $N_e^{FB}$ , such that the total social benefits are maximized:

$$(10) \quad TSB^{FB} = \max_{\bar{N} \geq N_e^{FB}} \left( \int_0^{N_e^\#} MSB_L dN_e + \int_{N_e^\#}^{N_e^{FB}} MSB_H dN_e \right)$$

Indeed, as used in (10), it is easy to prove that, under zero marginal cost, the first-best level of technology penetration,  $N_e^{FB}$ , is always in the range  $N_e^\# < N_e^{FB} \leq \bar{N}$ , implying that some equipped drivers arrive before  $t^*$ .<sup>10</sup> Thus, the socially optimal level of technology penetration  $N_e^{FB}$  is then derived by

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<sup>10</sup>  $MSB$  is a discontinuous function which might cross marginal cost line of zero in two points: in the low and high ranges of penetration  $N_e$ . We compared the two integrals of  $MSB$ , one where the upper limit corresponds to the point of intersection in the low range, and one in the high range. The latter integral is always larger than the former. This also holds when  $MSB$  crosses the horizontal line only in the low range, while in the high range it ends up in the corner solution.

equating  $MSB_H$  to zero.<sup>11</sup> If the corner solution  $N_e^{FB} = \bar{N}$  holds, a competitive market provides the optimal outcome. Otherwise,  $TSB^{PC} < TSB^{FB}$ , meaning that taxation is required to achieve higher social welfare, by bringing down the number of equipped drivers from  $\bar{N}$  to  $N_e^{FB}$ .<sup>12</sup>

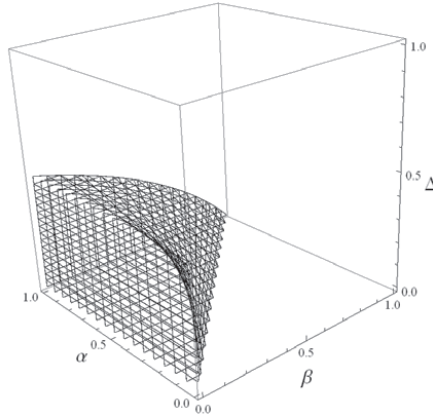
When comparing the outcomes of perfect competition and first-best, some results turn out to be cumbersome to present algebraically, so in this section we present results graphically, on the basis of numerical computations. In this model, numerical analysis can in fact be rather exhaustive, because all functions that are necessary for the analysis are dependent only on four parameters  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\Delta$ . Without loss of generality, we may normalize the opportunity cost of being late at workplace as  $\gamma = 1$ . The model restricts the effect from teleworking to  $\Delta \in (0, \gamma)$ . Most of the empirical literature suggests the relationship  $\gamma > \alpha > \beta$  (e.g., Small, 1982). The relevant parameter space might then be shown as a cube with the edges  $\alpha$ ,  $\beta$  and  $\Delta$ , each of a length 1 (if desired, one could easily relax the constraint to allow both  $\alpha$  and  $\beta$  to be larger than  $\gamma$ ). Without loss of generality, we normalize the overall number of drivers  $\bar{N}$  to 100, and set road capacity  $s$  to 1, so that the duration of the peak is 100. This does not affect the results of interest. In subsequent computations we define the beginning of the day  $t_s$  as the arrival time of the first driver when no teleworking is available (see equation (2)). We can safely do this, because an introduction of teleworking always shifts the arrival window to later times. The reallocation of  $t_s$  to an earlier stage increases the ideal utility  $I_e$ , as the time during which drivers are able to gain benefits from teleworking expands. But the increase takes place over a period where no one travels under any equilibrium, and we like to keep this “benefit” as small as possible. Changes in the end time  $t_F$  do not affect the comparative performance of equilibria with and without teleworking, as this involves times of the day where only  $W(t)$  matters for overall welfare, and this is not affected by the adaptation of the technology.

<sup>11</sup> The socially optimal equilibrium level of technology penetration is  $N_e^{FB} = \frac{\beta\Delta(2\alpha-2\beta+\Delta-\gamma)\bar{N}+\alpha(\beta+\gamma)\Delta(t^*-t_s)}{2(\alpha-\beta)\Delta(\beta-\Delta+\gamma)}$ , as derived from setting the  $MSB_H$  to zero, where  $MSB_H = MWTP + MSB_e + MSB_u$ , given  $N_e^\# < N_e^{FB} \leq \bar{N}$ .

<sup>12</sup> When marginal costs are positive and large enough, it might be possible that perfect competition will supply less than the optimal number of drivers, and then a subsidy is appropriate. After deriving equations of  $MWTP$  and  $MSB$  it follows that if marginal costs are larger than  $\Delta(t^* - t_s) - \frac{\beta\Delta(\gamma-\Delta)\bar{N}}{(\alpha+\Delta)(\beta+\gamma)s'}$ , then the competitive technology penetration level falls short of social optimal one,  $N_e^{PC} < N_e^{FB}$ .

Figure 2.5 shows the domain of parameters values which make the perfect competition outcome of full penetration of the teleworking technology socially less desirable than the first-best outcome. The combinations of  $\alpha$ ,  $\beta$  and  $\Delta$  within the meshed body are those for which  $TSB^{PC} < TSB^{FB}$ . The domain outside the meshed body in Figure 2.5, in so far as it complies with the restriction  $\alpha > \beta$ , corresponds to the values where the competitive market generates the first-best outcome.

**Figure 2.5.** Parameter combinations that correspond to an above-optimal level of teleworking penetration under perfect competition,  $\gamma = 1$



To better understand the conditions under which perfect competition could lead to an above-optimal penetration level, as in the meshed body in Figure 2.5, we compare the private benefits of the last unequipped driver when she gets equipped, with the negative externality on all other drivers she imposes. One can easily derive the condition for perfect competition, i.e.,  $N_e = \bar{N}$ , to yield the first-best welfare gain (again, when the marginal costs are zero):

$$(11) \quad \Delta \geq \frac{\alpha - \beta}{2\alpha - \beta}$$

given that  $\gamma = 1$ . When  $\beta \rightarrow 0$ , this condition becomes  $\Delta > 0.5$ . If  $\beta \rightarrow \alpha$ , then it becomes  $\Delta > 0$ . To see the intuition behind this pattern, not that the reason why



perfect competition might not lead to the first-best outcome is that there is a difference between external costs that unequipped drivers impose on others (both equipped and unequipped), and the external costs from equipped drivers. That difference, conditional on  $\Delta$ , is small when  $\beta \rightarrow \alpha$ ; and at the limit, when  $\beta = \alpha$ , it disappears completely. This happens because the slopes of isocost lines of early arrivals of both equipped and unequipped drivers become identical:  $\frac{\beta}{\alpha} = \frac{\beta + \Delta}{\alpha + \Delta} = 1$ . This means that both groups trade-off travel delay and schedule delay costs identically, that the groups are not separated in time, and thus impose the same external costs on each other. An individual decision to become equipped then does not imply a change in the individual's external cost, so that as long as the individual herself benefits from doing so, also the net social welfare gain is positive. Even a small positive  $\Delta$  is then enough to make full penetration of teleworking socially beneficial. However, when the difference in slopes of isocost lines between equipped and unequipped becomes larger ( $\alpha$  and  $\beta$  diverge), implying larger differences in imposed negative externalities, a bigger gain  $\Delta$  is required to "compensate" for larger net external costs imposed, and to make full penetration also socially optimal. At the limit, when  $\beta \rightarrow 0$ , the corresponding  $\Delta$  is 0.5. This explains the shape of the body in Figure 2.5. The value of  $\gamma$  is irrelevant, as the difference between negative externalities of equipped and unequipped drivers under perfect competition is determined by the slopes of early arrivals.

#### 4.2 Private monopoly

A private monopolistic provider is assumed to set the profit maximizing price. The profit of the monopolist ( $\Pi^M$ ), given zero marginal costs, and ignoring fixed costs, is the maximized integral of the marginal revenue ( $MR$ ) function, which itself directly follows from the  $MWTP$  function. For both ranges of levels of technology penetration, high and low,  $MR$  is twice as steep as the  $MWTP$ . The monopolist's profit is:

$$(12) \quad \Pi^M = \begin{cases} \int_0^{N_e^M} MR_L dN_e & \left| \begin{array}{l} 0 \leq N_e^M \leq N_e^\# \\ N_e^\# < N_e^M \leq \bar{N} \end{array} \right. \\ \int_0^{N_e^\#} MR_L dN_e + \int_{N_e^\#}^{N_e^M} MR_H dN_e & \end{cases}$$

where the number of equipped drivers under monopoly is  $N_e^M = \underset{N_e}{\operatorname{argmax}} \Pi^M$ .

In the numerical computations, we set the  $MR$  function to zero, and check for the corresponding profit. Depending on the parameter values,  $MR$  might cross in both ranges of technology penetration (high and low), and then we numerically check for the largest resulting profit. The corresponding total social benefits ( $TSB^M$ ) is then the integral of marginal social benefits, with  $N_e^M$  as the upper limit:

$$(13) \quad TSB^M = \begin{cases} \int_0^{N_e^M} MSB_L dN_e & \left| 0 \leq N_e^M \leq N_e^\# \right. \\ \int_0^{N_e^\#} MSB_L dN_e + \int_{N_e^\#}^{N_e^M} MSB_H dN_e & \left| N_e^\# < N_e^M \leq \bar{N} \right. \end{cases}$$

Because  $MR$  and  $MSB$  are not equal, the monopolist matches the first-best outcome only when achieving full penetration; i.e., when monopolist ends up in the corner solution of  $N_e^M = \bar{N}$ . This requires  $MR$  to be high enough; for instance, when  $\Delta$  is large.

As observed in Section 2.3,  $MSB$  always exceeds  $MR$ ; therefore, the private monopolist will never supply more than the optimal number of drivers with the teleworking technology. One underlying reason is that the private provider internalizes the negative external effects that its customers impose upon one another. The positive externalities of teleworking to unequipped drivers are, however, left outside the monopolistic pricing rule while it would reduce the socially optimal price, implying that the profit-maximizing price exceeds the welfare-maximizing price also for a reason different from the classic demand-related mark-up. We can summarize our findings on the level of penetration under different market forms in Proposition 3.

**Proposition 3.** Given zero marginal costs, equilibrium levels of technology penetration under different market forms relate to each other in the following manner:  $N_e^M \leq N_e^{FB} \leq N_e^{PC}$ .

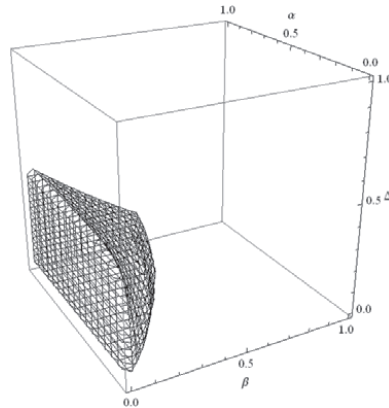
**Proof.** See Appendix.

Next, in Figure 2.6 we compare the welfare outcomes of perfect competition versus the private monopoly. The combination of  $\alpha$ ,  $\beta$  and  $\Delta$  within the meshed body are those for which  $TSB^{PC} < TSB^M$ , so monopoly produces a higher social welfare than perfect competition does. The parameter space

outside the meshed body, insofar as  $\alpha > \beta$ , corresponds to the values where either perfect competition outperforms monopoly, or where both yield the same outcome in terms of social welfare.

For a sizable parameter space, a monopoly market leads to a higher social welfare than perfect competition. The body of Figure 2.6 lies entirely within that of Figure 2.5. That is: total social benefits under monopoly can be larger than under perfect competition only if perfect competition itself is not the first-best outcome. If the strict inequality  $N_e^M < N_e^{FB} < N_e^{PC}$  holds, the monopoly level of penetration might be “closer” (in terms of welfare) to the first-best level than perfect competition, as the latter always produces  $\bar{N}$ . Figure 2.6 shows that perfect competition is particularly “harmful” in terms of oversupply when the differences between external effects of unequipped on equipped vs. equipped on themselves is large; i.e., when  $\beta$  diverges from  $\alpha$ . Not shown explicitly in Figure 2.6 is the subset of parameter values where the monopolist prefers to be in the low range of penetration; i.e.  $0 \leq N_e^M \leq N_e^\#$ . That area touches the one shown in Figure 2.6, and is located in the bottom part (low  $\Delta$ ), in the corner with high  $\alpha$  and  $\beta$  (but  $\alpha > \beta$ ). There, the resulting  $TSB^M$  is so low, that oversupply of perfect competition is socially preferable.

**Figure 2.6.** Parameter combinations that have a larger total social welfare under monopoly than under perfect competition,  $\gamma = 1$



Small (1982) was the first to provide empirical values for the parameters  $\alpha$ ,  $\beta$  and  $\gamma$ , which suggest that their relative values approximately satisfy:  $\gamma =$

$2\alpha = 4\beta$ . This combination of parameter values turns out to be within the body displayed in the Figure 2.6 for relatively low values of  $\Delta$ . This suggests that monopolistic supply of the teleworking technology might be more attractive than competitive supply for moderate values of  $\Delta$ , which in turn would reflect limited attractiveness of working at home with the technology, compared to being at work. For example, for the parameter values  $\gamma = 1$ ,  $\alpha = 0.5$ ,  $\beta = 0.25$  and  $\Delta = 0.125$ , the equilibrium levels of technology penetration and corresponding total welfare levels under, respectively, perfect competition, welfare maximization and monopoly are  $N_e^{PC} = 100$ ,  $N_e^{FB} = 72.2(2)$ ,  $N_e^M = 61.1(1)$  and  $TSB^{PC} = 375$ ,  $TSB^{FB} = 418.4$  and  $TSB^M = 411.5$ .

## 2.5 Teleworking with the first-best road toll

We have now established how, in the presence of congestion, the use of teleworking technology by equipped drivers causes externalities for others. A consequence is that it may not be optimal to supply the technology at marginal production cost; zero, in our case. The second-best distortion that is responsible for this, is the unpriced congestion at the bottleneck. A relevant question is whether the externality in the consumption of the technology, and hence the optimal deviation from marginal cost pricing for the purchase, vanishes when congestion at the bottleneck is optimally priced.

A central result in the literature on Vickrey's dynamic bottleneck model is that waiting time is a pure social loss, which can be fully eliminated through optimal time-varying pricing (Vickrey, 1969; Arnott, de Palma and Lindsey, 1993). The social optimum is achieved by levying a first-best time-dependent road toll that exactly equals the travel delay costs in the no-toll equilibrium, at each moment of arrival. Thus, instead of waiting in the queue, drivers pay a toll and incur no waiting time. With homogeneous drivers, the generalized travel price thus remains unchanged, compared to the no-toll case considered earlier. But from the social viewpoint, a toll is not a cost component, but a welfare neutral monetary transfer from road users to government. The welfare gain from first-best pricing is therefore equal to the total toll revenues, and therewith to the total savings in travel delay cost. For more in-depth discussion of the model with pricing we refer to, among others, Arnott, de Palma and Lindsey (1993).

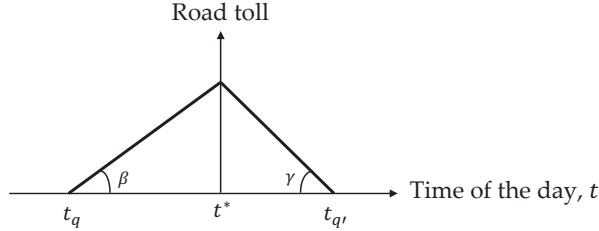
**Figure 2.7.** Isoprice function of the homogeneous drivers

Figure 2.7 shows the optimal toll schedule for homogeneous unequipped drivers. The schedule depends entirely on the parameters  $\beta$ ,  $\gamma$ ,  $s$  and  $\bar{N}$ . Note that the peak starts at the same time  $t_q$  as in the no-toll case, because the very first and the very last driver in both regimes incur schedule delay costs only, which should be equalized also in the optimum. The generalized price of travel is therefore also equal to that in the no-toll equilibrium. The toll schedule has slopes  $\beta$  and  $-\gamma$  to keep the price constant over time without a queue, and reaches its maximum at the preferred arrival time.

Figure 2.7 represents the isoprice function, and thus resembles Figure 2.2 for the no-toll case, the only difference being the slopes. These are  $\beta$  and  $-\gamma$  with first-best pricing, and  $\frac{\beta}{\alpha}$  and  $-\frac{\gamma}{\alpha}$  in the no-toll equilibrium. This difference only reflects the different units used in the vertical dimension (money in Figure 2.7 versus time in Figure 2.2).

It is now straightforward to repeat the entire analysis from the section 2.3, under the new conditions of optimal road pricing. The slopes of the isoprice curves for early arrivals and for the late ones are, respectively,  $\beta$  and  $-\gamma$  for unequipped drivers, and  $\beta + \Delta$  and  $-(\gamma - \Delta)$  for equipped ones. The isoprice slope is flatter for equipped drivers for late arrivals and steeper for early ones. Thus, a temporal separation in arrival times of equipped and unequipped drivers occurs in qualitatively the same manner as in the no-toll case: unequipped travelers go first, equipped ones go last.

Furthermore, we can calculate *MWTP* and *MSB* in the same way as described in, respectively, subsections 2.3.1 and 2.3.2. It can be proven that the revenues from the toll collection are equal to the aggregate schedule delay cost, so that the average toll is exactly 50 percent of the average generalized price that all drivers incur in the optimum (as is true in the conventional bottleneck

model with homogeneous users), irrespective of  $N_e$  (the proof is available upon request). However, when  $\Delta$  is not zero and  $N_e < \bar{N}$  (i.e., not every driver is equipped), the peak shifts due to the imposition of optimal pricing<sup>13</sup> and it is not true that social cost of travel decreases by exactly 50 percent due to the optimal toll, as is true for the conventional bottleneck model with linear schedule delay costs. We find that the  $MWTP$  and  $MSB$  functions are identical:

$$(14) \quad MWTP = MSB = \Delta(t^* - t_s) + \frac{\beta\Delta}{\beta + \gamma} \frac{\bar{N}}{s} - \frac{\Delta(\beta + \gamma - \Delta)}{\beta + \gamma} \frac{N_e}{s}$$

The equality of  $MWTP$  and  $MSB$  implies that the teleworking technology becomes a conventional good when the congestion externality is perfectly internalized by the first-best road toll. That is, no policy interventions are required to bring  $MSB$  equal to the marginal costs under perfect competition. Equilibrium technology penetration under perfect competition corresponds to socially optimal one, and is derived by setting equation (14) to zero, which results in  $N_e^{PC} = N_e^{FB} = \bar{N}$ . And under monopoly, the regular overpricing due to market power occurs. Conventionally, in case of monopoly the equilibrium share of equipped drivers is exactly half of that under the first-best, i.e.,  $N_e^M = 0.5\bar{N}$ , as the slope of MR function is twice as steep as that of  $MWTP$ .

Finally, note that for both low ( $0 \leq N_e \leq N_e^\#$ ), and high numbers ( $N_e^\# < N_e \leq \bar{N}$ ) of equipped drivers, the functions are the same, i.e., there is now no kink in  $MWTP$ , and no discontinuity in the  $MSB$ . The reason why the kink in  $MWTP$  disappears is that equipped drivers impose an identical unpriced “net” externality, i.e., in excess of the toll level, namely zero under first-best pricing, whether they arrive after or before  $t^*$ . It was the difference in unpriced externalities imposed by early versus late equipped drivers that caused the kink for the no-toll case, and this difference now no longer exists with optimal pricing. This result is shown generally by Arnott and Kraus (1998).

## 2.6 Summary and conclusions

We investigated the welfare effects from teleworking becoming available for a congested bottleneck, using Vickrey’s (1969) dynamic bottleneck model.

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<sup>13</sup> Travel begins earlier in the social optimum, with the difference in start times of  $\frac{\beta\Delta}{\alpha(\beta+\gamma)} \frac{N-N_e}{s}$ .

We thank Robin Lindsey for pointing this out.

Teleworking was modeled as an increase in the utility that a person derives from being at home, sufficiently small to keep commuting worthwhile. We derived the marginal willingness to pay for teleworking as the difference in utility that a driver gains when being equipped with teleworking-enabling technology, compared to being unequipped. Getting the possibility of teleworking creates differences in the utility parameters of otherwise homogeneous drivers, and therefore affects their dynamic travel behavior.

As compared to unequipped drivers, an equipped driver values being at home relatively high, while late arrival becomes relatively less problematic, as she can “compensate” being late by working from home. Thus, we show that equipped drivers depart from home “at the end of the peak” to gain the most out of teleworking. But the rising number of the equipped drivers makes the end of traffic jam increasingly late, and thus diminishes teleworking benefits and therewith the marginal willingness to pay for it. As the marginal external costs differ between equipped and unequipped drivers, the decision to become equipped influences travel costs of all other drivers.

We derive generalized travel costs for both equipped and unequipped drivers, and the total social benefits of teleworking as a function of the number of equipped drivers. The optimal level of technology penetration is then such that the marginal social benefit is equal to the marginal social cost. We compared the relative efficiency of private market outcomes, under monopoly and perfect competition, to the social optimum. Finally, we examined the effect of teleworking on travel costs when the congestion externality is internalized using the time-dependent first-best road toll.

We find that even costless teleworking might have an adverse marginal effect on social welfare, when a certain level of technology penetration is reached, due to the negative externality it creates. The very first unequipped driver who becomes equipped prefers to be the only one teleworking, as equipped drivers impose higher external travel cost on one another than unequipped impose on them. The more people are teleworking, therefore, the lower the benefits of teleworking for each individual equipped driver. The remaining unequipped drivers enjoy positive effects of teleworking: the negative externality of equipped drivers on unequipped ones is lower than what unequipped drivers impose up on one another. Although full penetration of costless teleworking is always socially more beneficial than no teleworking at

all, there exists an optimal degree of driver heterogeneity. An increase in the number of equipped drivers above that level lowers social welfare.

Our results show that a private monopolistic supplier of a teleworking technology might yield a higher social welfare than perfect competition does. Under perfect competition, with zero marginal cost, all drivers are teleworking, as the endogenous marginal willingness to pay for teleworking is always positive. A full penetration might, however, be socially excessive. At the same time, a monopolist charges a mark-up, while taking into account the negative effects its customers impose on each other, ignoring the positive effects on unequipped drivers. The level of penetration under monopoly could consequently be below the optimal level. We identified the conditions under which the monopoly outcome is “closer” to optimal, from a social welfare viewpoint, than that of perfect competition.

A policy that would eliminate the congestion externality would also get rid of the changes in externalities resulting from the purchase of the technology. Time-dependent first-best road toll achieves this, and makes the teleworking technology a conventional good, which does not require any policy intervention.

To the best of our knowledge, this study is the first to model the effect of (part-day) teleworking on generalized travel costs. We have used a conventional linearized scheduling model, as considered by Vickrey (1969), Small (1982), Arnott et al. (1993), but we assumed it stems from preferences of being at home and being at work in a way as described by Vickrey (1973) and, later, by Tseng and Verhoef (2008). We found this framework suits well for the analysis and yields interesting insights.

There is ample scope for further research on the effects of teleworking on travel within the considered framework. Among the possible extensions are a consideration of initial driver heterogeneity; variation in teleworking technology; and more complex road networks allowing for an explicit consideration of spatial and network effects, in addition to the temporal dimension considered here. It might also be interesting to incorporate other effects of teleworking besides those on travel costs, such as effects on productivity, work-life balance, etc., to get the full picture of the overall effect of teleworking on welfare.



## Appendix

**Lemma 1.** The generalized travel costs for unequipped drivers  $P_u$  is decreasing when the share of equipped drivers  $N_e$  rises, i.e.,  $\frac{\partial P_u}{\partial N_e} < 0$ .

**Proof.** The proof consists of two parts – the first part proves Lemma 1 for the “low” range of  $N_e$ , i.e.,  $0 \leq N_e \leq N_e^\#$ , the second proves for the “high” range, i.e.,  $N_e^\# < N_e \leq \bar{N}$ .

For the first part, to calculate equilibrium cost levels as a function of  $N_e$ , we indicate the travel delay that the first arrived equipped driver incurs as  $X$ , while  $Y$  gives the absolute difference between  $X$  and the travel delay of a driver who arrives at work at time  $t^*$ . We can write  $X$  and  $Y$  as follows:

$$(A1) \quad X + Y = \frac{\beta N_u^E}{\alpha s} = \frac{\beta \bar{N} - N_e - N_u^L}{\alpha s}$$

$$(A2) \quad X = \frac{\gamma - \Delta N_e}{\alpha + \Delta s}$$

$$(A3) \quad Y = \frac{\gamma N_u^L}{\alpha s}$$

These equalities can easily be verified in Figure 2.3. After substituting (A2) and (A3) into (A1), we can express  $\frac{N_u^L}{s}$  (i.e., the duration of the interval where unequipped drivers arrive after  $t^*$ ) and  $\frac{N_u^E}{s}$  (i.e., the duration of the peak before  $t^*$ ) as a function of  $N_e$ :

$$(A4) \quad \frac{N_u^L}{s} = \frac{\beta}{\beta + \gamma} \frac{\bar{N}}{s} - \frac{(\alpha + \Delta)\beta + \alpha(\gamma - \Delta)}{(\alpha + \Delta)(\beta + \gamma)} \frac{N_e}{s}$$

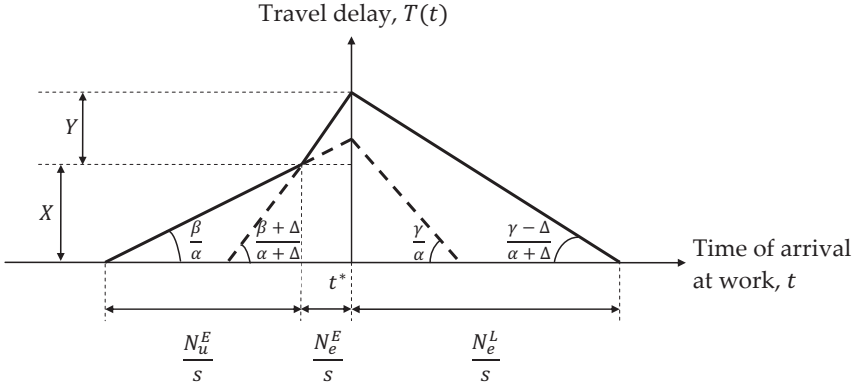
$$(A5) \quad \frac{N_u^E}{s} = \frac{\gamma}{\beta + \gamma} \frac{\bar{N}}{s} - \frac{\Delta(\alpha + \gamma)}{(\alpha + \Delta)(\beta + \gamma)} \frac{N_e}{s}$$

Multiplying (A5) by  $\beta$ , we get the generalized travel costs of unequipped drivers as a function of  $N_e$  (for  $0 \leq N_e \leq N_e^\#$ ):

$$(A6) \quad P_u = \frac{N_u^E}{s} \beta = \frac{\gamma \beta}{\beta + \gamma} \frac{\bar{N}}{s} - \frac{\Delta \beta (\alpha + \gamma)}{(\alpha + \Delta)(\beta + \gamma)} \frac{N_e}{s}$$

Since all Greek characters symbolize positive parameters, and  $s$  is positive too, equation (A6) shows that  $\frac{\partial P_u}{\partial N_e} < 0$ , for the “low” range of  $N_e$ .

**Figure 2.A.** Isocost functions of the heterogeneous drivers, if equipped drivers arrive at work late and early



The logic of the derivation of  $P_u$  stays the same for the “high” range, i.e.,  $N_e^\# < N_e \leq \bar{N}$ . Let  $N_e^E$  be the number of equipped drivers arriving early, and  $N_e^L$  the number arriving late, so that  $N_e = N_e^E + N_e^L$ . For the present case  $N_e^\# < N_e \leq \bar{N}$ , we can express  $X$  and  $Y$ , as shown in Figure 2.A, as:

$$(A7) \quad X + Y = \frac{\gamma - \Delta}{\alpha + \Delta} \frac{N_e^L}{s} = \frac{\gamma - \Delta}{\alpha + \Delta} \frac{\bar{N} - N_u^E - N_e^E}{s}$$

$$(A8) \quad X = \frac{\beta}{\alpha} \frac{N_u^E}{s} = \frac{\beta}{\alpha} \frac{\bar{N} - N_e^E - N_e^L}{s}$$

$$(A9) \quad Y = \frac{\beta + \Delta}{\alpha + \Delta} \frac{N_e^E}{s}$$

After substituting (A8) and (A9) into (A7), we derive  $\frac{N_e^E}{s}$  (i.e., the duration of the interval when equipped drivers arrive early) and  $\frac{N_e^L}{s}$  (i.e., the duration of the peak after  $t^*$ ):

$$(A10) \quad \frac{N_e^E}{s} = -\frac{(\alpha + \Delta)\beta}{\alpha(\beta + \gamma)} \frac{\bar{N}}{s} + \frac{(\alpha + \Delta)\beta + \alpha(\gamma - \Delta)}{\alpha(\beta + \gamma)} \frac{N_e}{s}$$

$$(A11) \quad \frac{N_e^L}{s} = \frac{(\alpha + \Delta)\beta}{\alpha(\beta + \gamma)} \frac{\bar{N}}{s} + \frac{(\alpha - \beta)\Delta}{\alpha(\beta + \gamma)} \frac{N_e}{s}$$

The generalized cost for unequipped drivers, become:

$$(A12) \quad P_u = \left( \frac{\bar{N}}{s} - \frac{N_e^L}{s} \right) \beta = \left( \frac{\bar{N}}{s} - \frac{(\alpha + \Delta)\beta \bar{N}}{\alpha(\beta + \gamma)s} - \frac{(\alpha - \beta)\Delta N_e}{\alpha(\beta + \gamma)s} \right) \beta$$

Equation (A12) shows that  $\frac{\partial P_u}{\partial N_e} < 0$ , for the “high” range of  $N_e$  (recall that  $\alpha > \beta$ ). ■

**Lemma 2.** The generalized travel costs of equipped drivers  $P_e$  is increasing when the share of equipped drivers  $N_e$  rises, i.e.,  $\frac{\partial P_e}{\partial N_e} > 0$ .

**Proof.** Using equations (A4) and (A11) we define the generalized travel costs of equipped drivers  $P_e$ , for, respectively, the “low” and “high” ranges of  $N_e$  as follows:

$$(A13) \quad P_e = \left( \frac{N_u^L}{s} + \frac{N_e}{s} \right) (\gamma - \Delta) = \frac{\beta(\gamma - \Delta) \bar{N}}{\beta + \gamma} \frac{1}{s} + \frac{\Delta(\gamma - \Delta)(\alpha + \gamma) N_e}{(\alpha + \Delta)(\beta + \gamma)s} \quad \left| 0 \leq N_e \leq N_e^\# \right.$$

$$(A14) \quad P_e = \frac{N_e^L}{s} (\gamma - \Delta) = \frac{(\gamma - \Delta)(\alpha + \Delta)\beta \bar{N}}{\alpha(\beta + \gamma)s} + \frac{(\alpha - \beta)\Delta(\gamma - \Delta) N_e}{\alpha(\beta + \gamma)s} \quad \left| N_e^\# < N_e \leq \bar{N} \right.$$

The lemma follows immediately from (A13) and (A14), given that  $\alpha > \beta$  and  $\gamma > \Delta$ . ■

**Proposition 1.** *MWTP* is negatively related to number of equipped drivers  $N_e$ , so if more drivers are equipped, an additional individual driver is willing to pay less for teleworking technology, i.e.,  $\frac{\partial MWTP}{\partial N_e} < 0$

**Proof.** For the “low” range of equipped drivers, we use equations (A6) and (A13) to derive utility of, respectively, unequipped and equipped drivers:

$$(A15) \quad U_u = \Gamma_u - P_u \\ = \alpha(t^* - t_S) + (\alpha + \gamma)(t_F - t^*) - \frac{\gamma\beta}{\beta + \gamma} \frac{\bar{N}}{s} + \frac{\Delta\beta(\alpha + \gamma)}{(\alpha + \Delta)(\beta + \gamma)} \frac{N_e}{s}$$

$$(A16) \quad U_e = \Gamma_e - P_e \\ = (\alpha + \Delta)(t^* - t_S) + (\alpha + \gamma)(t_F - t^*) - \frac{\beta(\gamma - \Delta) \bar{N}}{\beta + \gamma} \frac{1}{s} \\ - \frac{\Delta(\gamma - \Delta)(\alpha + \gamma) N_e}{(\alpha + \Delta)(\beta + \gamma)s}$$

We plug in equations (A15) and (A16) into equation (5) to derive  $MWTP$  when  $0 \leq N_e \leq N_e^\#$ :

$$(A17) \quad \begin{aligned} MWTP &= U_e - U_u = \Gamma_e - P_e - \Gamma_u + P_u \\ &= \Delta(t^* - t_s) + \frac{\beta \Delta}{\beta + \gamma} \frac{\bar{N}}{s} - \frac{\Delta(\beta + \gamma - \Delta)(\alpha + \gamma)}{(\alpha + \Delta)(\beta + \gamma)} \frac{N_e}{s} \end{aligned}$$

Equation (A17) shows that  $\frac{\partial MWTP}{\partial N_e} < 0$  (recall that  $\gamma > \Delta$ ).

For the “high” range of equipped drivers, we use equations (A12) and (A14) to derive utility of, respectively, unequipped and equipped drivers:

$$(A18) \quad \begin{aligned} U_u &= \Gamma_u - P_u \\ &= \alpha(t^* - t_s) + (\alpha + \gamma)(t_F - t^*) \\ &\quad - \left( \frac{\bar{N}}{s} - \frac{(\alpha + \Delta)\beta \bar{N}}{\alpha(\beta + \gamma)s} - \frac{(\alpha - \beta)\Delta N_e}{\alpha(\beta + \gamma)s} \right) \beta \end{aligned}$$

$$(A19) \quad \begin{aligned} U_e &= \Gamma_e - P_e \\ &= (\alpha + \Delta)(t^* - t_s) + (\alpha + \gamma)(t_F - t^*) - \frac{(\gamma - \Delta)(\alpha + \Delta)\beta \bar{N}}{\alpha(\beta + \gamma)s} \\ &\quad - \frac{(\alpha - \beta)\Delta(\gamma - \Delta) N_e}{\alpha(\beta + \gamma)s} \end{aligned}$$

We plug in equations (A18) and (A19) into equation (5) to derive  $MWTP$  when  $N_e^\# < N_e \leq \bar{N}$ :

$$(A20) \quad \begin{aligned} MWTP &= U_e - U_u = \Gamma_e - P_e - \Gamma_u + P_u \\ &= \Delta(t^* - t_s) - \frac{\beta \Delta(\beta - \alpha + \gamma - \Delta) \bar{N}}{\alpha(\beta + \gamma)s} - \frac{\Delta(\beta + \gamma - \Delta)(\alpha - \beta) N_e}{\alpha(\beta + \gamma)s} \end{aligned}$$

Equation (A20) shows that  $\frac{\partial MWTP}{\partial N_e} < 0$  (recall that  $\alpha > \beta$  and  $\gamma > \Delta$ ). ■

**Proposition 2.** The slope of the  $MSB$  function is twice as steep as the slope of the  $MWTP$ .

**Proof.** Let  $TSC$  be the total social costs,  $\varphi = \frac{\partial P_u}{\partial N_e}$ , and  $\mu$  and  $\theta$  are constants to be defined below. Following equations (A6), (A12), (A13), (A14) we can write the difference in generalized travel costs as a function of the number of equipped drivers  $N_e$ :

$$(A21) \quad P_u - P_e = \mu \bar{N} - \theta N_e$$

with

$$\mu = \begin{cases} \frac{\beta\Delta}{(\beta+\gamma)s}, & | 0 \leq N_e \leq N_e^\# \\ \frac{\beta\Delta(\alpha-\beta-\gamma+\Delta)}{\alpha(\beta+\gamma)s}, & | N_e^\# < N_e \leq \bar{N} \end{cases}$$

$$\theta = \begin{cases} \frac{\Delta(\alpha+\gamma)(\beta-\Delta+\gamma)}{(\alpha+\Delta)(\beta+\gamma)s}, & | 0 \leq N_e \leq N_e^\# \\ \frac{\Delta(\alpha-\beta)(\beta-\Delta+\gamma)}{\alpha(\beta+\gamma)s}, & | N_e^\# < N_e \leq \bar{N} \end{cases}$$

For both “low” and “high” ranges of the technology penetration we can write *MWTP* as:

$$(A22) \quad MWTP = U_e - U_u = (\Gamma_e - P_e) - (\Gamma_u - P_u) = \Gamma_e - \Gamma_u + P_u - P_e = \Delta(t^* - t_s) + \mu\bar{N} - \theta N_e.$$

*TSC* is the sum of the costs of equipped and unequipped drivers:

$$\begin{aligned} TSC &= N_u P_u + N_e P_e = (\bar{N} - N_e) P_u + N_e P_e = \bar{N} P_u + N_e (P_e - P_u) \\ &= \bar{N} P_u + N_e (\theta N_e - \mu \bar{N}) \end{aligned}$$

Note that by definition  $MSB = -\frac{\partial TSC}{\partial N_e} + (\Gamma_e - \Gamma_u)$ ; that leads to:

$$\begin{aligned} -MSB &= \frac{\partial TSC}{\partial N_e} - (\Gamma_e - \Gamma_u) = \bar{N} \frac{\partial P_u}{\partial N_e} + 2\theta N_e - \mu \bar{N} - \Delta(t^* - t_s) \\ &= \varphi \bar{N} + 2\theta N_e - \mu \bar{N} - \Delta(t^* - t_s) \end{aligned}$$

From equations (A6) and (A12) we see that  $\varphi$  is a (negative) constant which does not depend on  $N_e$ , hence the slope of the *MSB* function is twice as steep as the slope of the *MWTP*:

$$(A23) \quad MSB = \Delta(t^* - t_s) + (\mu - \varphi)\bar{N} - 2\theta N_e \quad \blacksquare$$

**Proposition 3.** Given zero marginal costs, equilibrium levels of technology penetration under different market forms relate to each other in the following manner:  $N_e^M \leq N_e^{FB} \leq N_e^{PC}$ .

**Proof.** *MWTP* of the last unequipped driver who becomes equipped is positive, as follows from equation (A20), i.e.,  $(MWTP|N_e = \bar{N}) > 0$ . Thus, under zero marginal costs, an equilibrium level of technology penetration under the perfect

competition is  $\bar{N}$ , as  $MWTP$  function is monotonously decreasing with respect to  $N_e$ .

Proposition 2 shows that the  $MSB$  function is twice as steep as the slope of the  $MWTP$ , but the intercepts are larger than those of  $MWTP$  (compare equations (A22) and (A23)).  $MR$  function is also twice as steep as the slope of the  $MWTP$ , however it has the same intercepts as the  $MWTP$  function. That makes  $MR$  function cross the horizontal line to the left of  $MSB$  function, implying  $N_e^M < N_e^{FB}$  (unless it is a corner solution when  $N_e^M = N_e^{FB} = \bar{N}$ ). ■



### 3 Dynamic bottleneck congestion and residential land use in the monocentric city

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#### 3.1 Introduction<sup>14</sup>

Peak-hour traffic congestion is a hardly avoidable burden in the morning routines for many residents in modern cities. Many commuters usually depart from home earlier than they would otherwise prefer to, in anticipation of the time they will spend in congestion. Time at home could have been spent on more sleeping, working, exercising, or other activities. Some of these would either require additional floor space or are better enjoyed in a more spacious environment. Long looked-for alleviation of congestion might thus, when leading to more time spent at home, affect not only the time allocation decisions of an inhabitant, but her spatial behavior as well. In this chapter, we show that first-best time-dependent road pricing not only relieves congestion but may also cause urban sprawl.

Congestion in an urban setting, where both spatial and travel behavior are endogenous, has proven to be a challenging topic for economic analysis (Ross and Yinger, 2000). By far the most common way of modeling congestion in such a setting is in terms of static flow congestion, where the timing of travel is not a choice variable, and where traffic flows and speeds are constant over time. For example, Solow and Vickrey (1971) relate the per-unit-of-distance cost of traveling at a certain location to the total number of drivers passing that point. That specification of travel cost does not allow the consideration of potential benefits of avoiding the peak by traveling earlier or later. But congestion in reality is a dynamic phenomenon, with time-varying speed and traffic flows. This has inspired transportation economists to develop dynamic models of traffic congestion, in which the choice of departure times is endogenous, and where dynamic patterns of travel delays are key features. As Vickrey showed in

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<sup>14</sup> This chapter is published in the *Journal of Urban Economics* (Gubins and Verhoef, 2014).



1969, such models may produce insights that diverge substantially from those traditional static models.

To develop a model that accounts for the dynamic nature of travel in a city, we integrate two workhorse models in the urban and transportation economics literature. A classic Alonso-Muth-Mills monocentric city model, in some important respects probably “the most successful model in urban economics” (Glaeser 2008, p. 18), defines the spatial equilibrium, in which no individual can unilaterally relocate within a city to gain a higher utility. Vickrey’s dynamic bottleneck model of peak period congestion, very likely the most widely used dynamic model of traffic congestion in transportation economics, allows for the analysis of a dynamic traffic equilibrium, in which no driver can gain a higher utility by unilaterally changing the departure time (see, for example, the exposition in Small and Verhoef, 2007). We aim to integrate those two models in order to study the relationship between spatial allocation and travel time decisions.

In our model, homogeneous inhabitants<sup>15</sup> with a common preferred time of arrival at work, commute from their homes to a workplace located in the central business district of a city (hereafter, the CBD). The city is congestion-free, apart from a road bottleneck right at the entrance to the CBD. One might think of a bridge or a junction that a driver has to pass to get to the workplace. Starting in a queue-free situation, when the inflow of cars first exceeds the bottleneck’s capacity, a queue starts growing in front of the bottleneck and evolves at a rate determined by the difference between queue-entries (at the back of the queue) and queue exits (the bottleneck’s capacity). By adjusting the timing of departure from home, a driver can incur different queuing times, and arrive at work at times with different levels of scheduling inconvenience. For instance, a driver can depart very early in the morning and avoid the queue altogether, or arrive at the most desirable moment but not after having spent quite some time in the queue. Following the framework of Vickrey (1973), and later Tseng and Verhoef (2008) and Fosgerau and Engelson (2011), we explicitly define the utility that an individual derives from spending time at home, at work, and in a car. That will later allow us to incorporate the spatial aspect of the model in a structured manner.

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<sup>15</sup> All city inhabitants are drivers, and we use both these terms to indicate the same individuals.

An important assumption that we introduce is that the marginal utility of spending time at home depends on the size of the house<sup>16</sup>, which is endogenously determined in the model. *Ceteris paribus*, the larger the house one lives in, the more utility one derives from spending additional time in it. This assumption seems consistent with the observed preferences for larger housing, as shown by countless hedonic price studies (see, e.g., Bajari and Kahn, 2008). We impose a time aspect by stating that an individual derives utility from a house by spending time in it. While a house might yield utility via various channels, e.g., as a storage place, a status symbol, or an investment asset, we believe it is safe to assume that at least some part of the utility from having a house depends on the amount of time an individual spends in it.<sup>17</sup> The usual pattern in the monocentric city model, with land consumption increasing the further away one lives from the CBD, thus produces variation in scheduling preferences across drivers, as a driver who lives closer to the CBD values time spent at home at a lower rate than one who lives at the city fringe. As we show later, depending on the size of the house, a driver chooses a certain time of departure from home, and vice versa. In this manner, we connect the transport model of bottleneck congestion, that has a dynamic equilibrium condition, with the urban model of a monocentric city, which gives a spatial equilibrium condition.

Arguably, the most striking result of this study is that first-best time-dependent road pricing in this context leads to a lower density, and hence a larger city, even without redistributing the collected road toll revenues back to the city inhabitants. The intuition is that first-best time-dependent road pricing induces drivers to spend more time at home, as road tolling eliminates queuing time by shifting departure times from home to later moments. More time spent at home provides stronger incentives for having a larger house, and thus the city expands. In a similar fashion, an expansion of bottleneck capacity leads to the same effect. Our outcome is the opposite of the typical result of spatial urban models with static flow congestion. There, the Pigouvian toll, the typical first-best remedy for the negative congestion externality, increases the generalized transportation costs, and therefore reduces the city's geographical extent (e.g., Wheaton, 1998; Anas et al., 1998). Nevertheless, our result is

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<sup>16</sup> Throughout the paper we use the consumption of "land" as equivalent to that of "housing" and therefore use both the words "land" and "house" consumption to indicate the same good.

<sup>17</sup> We check the sensitivity of our results with respect to this assumption later in the paper.

consistent with other results in the sense that improved transportation causes urban sprawl (see, for example, the paper by Glaeser and Kahn (2004) on the invention of cars, and the study by Baum-Snow (2007) on highways construction).

There are few economics papers that model dynamic congestion in urban space. Arnott and DePalma (2011) report on their progress to solve the so-called “corridor problem”, in which inhabitants of a monocentric city might experience congestion at each point on the road, as opposed to the single point congestion considered in this chapter. Finding a complete solution to the dynamic equilibrium of flow congestion without a toll appears prohibitively difficult, even in a setting with an exogenously distributed population. A paper by Arnott (1998) is the only one that considers both dynamic congestion in the form of Vickrey’s bottleneck and a (discrete) locational choice endogenously. The specified preference for the lot size though does not relate to the scheduling behavior and, as noted by Fosgerau and de Palma (2012), space in the model by Arnott (1998) has been “essentially [...] assumed away” (p. 274). Fosgerau and de Palma (2012) consider a continuous space city with a central Vickrey bottleneck, with time-varying marginal utilities of spending time at home and at work and without considering spatial equilibrium. Contrary to what we will find, they show that inhabitants located near the bottleneck tend to lose from optimal pricing. To the best of our knowledge, our study is the first to consider both locational choice (that leads to commuting) and scheduling choice (that affects residential location) of city inhabitants endogenously.

The chapter is organized as follows. Section 3.2 presents the model setup, and Section 3.3 discusses how to find the market equilibrium. Section 3.4 then shows the resulting equilibrium patterns of land consumption, population density and rents over space; as well as the dynamic travel patterns by location. Section 3.5 considers first-best time-varying road pricing. Section 3.6 studies the robustness of the numerical outcomes by performing sensitivity analyses. Section 3.7 concludes.

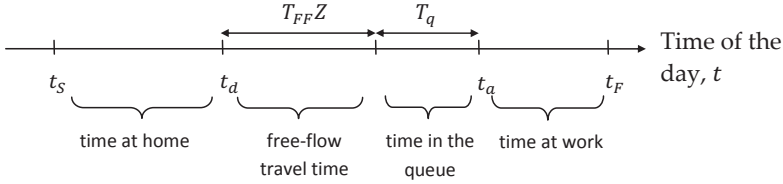
### 3.2 Model setup

Consider a closed linear rectangular city of  $n$  homogeneous, atomistic, car owning, utility-maximizing inhabitants. All inhabitants earn an identical wage  $m$  in a spaceless CBD which is located in the city center. Assuming symmetry,

we may consider half a city with the CBD being at the spatial edge of our single dimension. The inhabitants, with a common preferred time of arrival at work  $t^*$ , commute in the morning by car from their homes to the CBD, on a single road at a constant free-flow speed. At the entrance of the CBD, the road has a traffic bottleneck with a fixed capacity  $s$ . When the inflow of cars at any moment exceeds  $s$ , a “first-in first-out” traffic jam builds up at the bottleneck. Without queuing, the total commuting (free-flow) travel time of a driver is proportional to the distance from her home to the CBD, as in the conventional uncongested monocentric model. With queuing, the total travel time of a driver is the sum of her free-flow travel time to the CBD, plus the waiting time that she incurs in the queue.

To model scheduling behavior, we apply the model proposed by Vickrey (1973), and later by Tseng and Verhoef (2008) and Fosgerau and Engelson (2011), in which, over the course of the morning, travelers derive utility from being at home and being at work. The morning starts for everyone at a common time  $t_s$ , chosen arbitrarily besides being such that everyone will depart from home to work later than  $t_s$ . At a certain time, a driver departs from home to work and drives at a free-flow speed to the CBD. Different locations of houses within a city imply different distances  $Z$  to the CBD and, therewith, different free-flow travel times  $T_{FF} \cdot Z$ , where  $T_{FF}$  is the time needed to cover one unit of distance ( $Z = 0$  denotes the location of the CBD). A driver arrives at the entrance of the CBD, and, depending on the length of a queue, if any, waits  $T_q$  minutes to pass the bottleneck. After passing the bottleneck, the driver immediately arrives at work. The morning finishes for the drivers at the common time  $t_F$ , which is again chosen such that all drivers are at the workplace at that time. Denote a driver’s departure time from home as  $t_d$ , and the arrival at work as  $t_a$ . Throughout the chapter, we measure clock time as time before  $t_F$ , which itself we set at  $t_F = 0$ . A higher time value thus indicates an earlier moment; i.e.,  $t_s \geq t_d \geq t_a \geq t_F = 0$ . Figure 3.1 shows an example of a morning schedule.

We explicitly define the marginal utilities of being at home, at work, and in a vehicle, so as to characterize the time pattern of activities in terms of utilities and opportunity costs. This approach is practical here, as it will later allow connecting the monocentric and the conventional bottleneck models in a structured manner. This conventional bottleneck model has a constant value of

**Figure 3.1.** Example of a morning schedule

travel delays ( $\alpha$ ), and constant values of schedule delay early ( $\beta$ ) and late ( $\gamma$ ). Tseng and Verhoef (2008) show that such preferences emerge when it is assumed that a driver  $i$ 's marginal utility of being at home,  $H_i$ , is constant over the period considered, and the marginal utility of being at workplace  $W(t)$  is piecewise constant with a discrete upward jump at time  $t^*$ .<sup>18</sup> We assume that this is the case, with identical preferences over drivers. More precisely, we assume that  $W(t) = w < H_i$  before  $t^*$  and  $W(t) = \hat{w} > H_i$  after  $t^*$ . The utility of being in a vehicle,  $V$ , is normalized to zero without loss of generality.<sup>19</sup> This utility structure results in several time-invariant values of opportunity costs that are relevant for the further analysis. In particular, the opportunity cost of being in a vehicle is  $H_i - V = \alpha_i$ , which can be interpreted as a value of travel time in the standard linear scheduling model. Opportunity cost of being at work before  $t^*$  is  $H_i - w = \beta_i$ , while being at home after  $t^*$  is  $\hat{w} - H_i = \gamma_i$ . The former is equivalent to a unit shadow price of schedule delay early, the latter to that of schedule delay late. We assume  $V < W(t)$  to rule out a situation in which a driver prefers to stay in the car after arriving at the CBD. Figure 3.2 depicts this utility structure.<sup>20</sup>

It is instructive to present briefly the basic derivations of a standard (spaceless) bottleneck model, in which  $Z = 0$  and  $H_i = H$  (for an in-depth discussion of the model and its limitations see Arnott et al., 1993). A peak

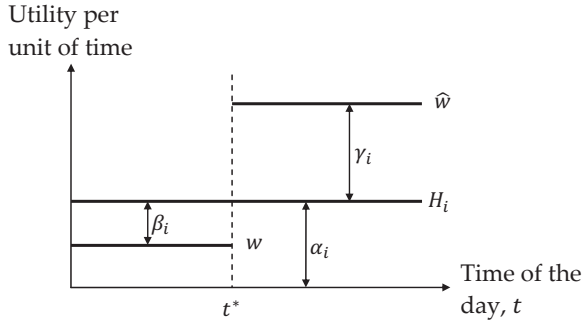
<sup>18</sup> We make  $H_i$  driver specific in anticipation of its endogeneity later on in the exposition.  $W(t)$  will remain uniform across drivers throughout the paper.

<sup>19</sup>  $H$ ,  $W$  and  $V$  are the values of the marginal willingness to pay for being at home, at work and in a car. For brevity we call them utilities.

<sup>20</sup> Alternative functional specifications of marginal utilities are possible, for instance, time-varying downward sloping  $H$  and upward sloping  $W$  functions (see Figure 1 in Tseng and Verhoef (2008)), which result in smooth time allocation. For example, Fosgerau and de Palma (2012) show that under that specification marginal utility of the last minute of being at home is equal to the marginal utility of the first minute of being at work. While our approach allows various specifications, we chose to stay as close as possible with the conventional linear (" $\alpha$ - $\beta$ - $\gamma$ ") scheduling model, which is widely used in the literature.

period of duration  $\frac{n}{s}$  is needed for all  $n$  drivers to pass the bottleneck. The very first and very last driver face no queuing delay and therefore have travel cost of, respectively,  $\beta(t^* - t_q) > 0$  and  $\gamma(t_{q'} - t^*) > 0$ , where  $t_q$  and  $t_{q'}$  are the

**Figure 3.2.** Utility structure and opportunity costs of a driver  $i$



Based on Tseng and Verhoef (2008), Figure 2.

beginning and the end of the peak period, and  $\frac{n}{s} = |t_{q'} - t_q|$ . In a dynamic equilibrium, all homogeneous drivers should incur the same generalized travel costs, irrespective of their arrival time  $t_a$ . That implies that the peak period starts at time  $t_q = t^* - \frac{\gamma}{\beta + \gamma} \frac{n}{s}$  and finishes at time  $t_{q'} = t^* + \frac{\beta}{\beta + \gamma} \frac{n}{s}$ , while the generalized travel cost is  $\frac{\gamma\beta}{\beta + \gamma} \frac{n}{s}$ . A driver who arrives at work at time  $t^*$ , incurs  $\alpha T_{qt^*}$  cost of travel delay, where  $T_{qt^*} = \frac{\gamma\beta}{\beta + \gamma} \frac{n}{s} \frac{1}{\alpha}$ . Between  $t_q$  and  $t^*$ , the queue grows linearly over time to equilibrate travel cost, while it shrinks linearly over time between  $t^*$  and  $t_{q'}$ . Thus, the bottleneck model highlights the trade-off that drivers make between waiting in a queue (travel delay cost) and arriving at an inconvenient time (schedule delay cost). This trade-off remains present in our spatial model.

We simplify the derivations considerably by setting schedule delay late  $\gamma_i$  prohibitively high. That is, no driver would choose to arrive at work after the preferred arrival time  $t^*$ . One might think of a typical beginning of the business hours at 9:00 am, which employees cannot miss without facing heavy costs. This allows us to set  $t^*$  equal to the end of the morning  $t_F$ , which simplifies

subsequent derivations at the moderate cost of fixing the start of the peak period, i.e., the peak period starts at time  $\frac{n}{s}$  and finishes at time  $t^* = t_F = 0$ . One can relax this assumption, as it does not affect the mechanics of the model.

A driver  $i$  derives Cobb-Douglas utility  $U$  from the way time is spent in the morning,  $X$ , and from consuming a numeraire good  $Q$ :

$$(1) \quad U_i = X_i^b Q_i^{1-b}$$

where  $X$  is the aggregated utility of time used at different locations, as it can be derived from the scheduling model used:

$$(2) \quad X_i = (t_S - T_{FF}Z_i - T_q(t_{ai}) - t_{ai})H_i + t_{ai}w$$

The first term on the right hand side of equation (2) is the utility one derives from being at home in the morning, while the second term is the utility from being at work before  $t^*$ . All city inhabitants consume some amount of the numeraire good  $Q$  at a price 1, under the budget constraint:

$$(3) \quad m = Q_i + r(Z_i)L(Z_i)$$

where  $L(Z_i)$  is the amount of land that an inhabitant consumes at location  $Z_i$ , with the rent  $r(Z_i)$  that an inhabitant pays to an absentee landlord. The key assumption of our model is that consumption of land  $L(Z_i)$  affects the marginal utility of being at home  $H_i$  in a positive way.

**Assumption 1.** *Ceteris paribus*, the larger the house one consumes, the higher is one's marginal utility of spending additional unit of time in it.

That is: a bigger house is assumed to bring higher utility, *ceteris paribus*, but we assume that this higher utility rises with the amount of time spent in the house. The probably simplest formulation incorporating this would be:

$$(4) \quad H_i = w + \varepsilon + \varphi L(Z_i)$$

where  $\varepsilon$  is a parameter that keeps the marginal utility of being at home above  $w$  even if  $L = 0$ , and  $\varphi$  is a parameter that “converts” the amount of land consumed into marginal utility values for spending time at home.

Assumption 1 is consistent with the observed preferences for larger housing, as shown by countless hedonic price studies (see, e.g., Bajari and Kahn, 2008). We add to that a time aspect, by assuming that an individual

derives more utility from a house when spending more time in it. While a house might yield utility via various channels – e.g., as a storage place, a status symbol, or an investment asset – we believe it is safe to assume that at least some part of the utility from housing depends on the amount of time an individual spends there. For our purposes, this is the only component of utility from housing that we need to (and will) specify.

We allow for endogenous variation in consumption of land. Rents are endogenously determined, to insure that inhabitants are indifferent between various locations within a city. That is, utility should be constant over space for a spatial equilibrium to be fulfilled. To close the model, we set the agricultural rent at the city fringe, and specify that demand for land matches supply at all locations. A pattern of land consumption over space results in a population density,  $(\frac{1}{L})$ , that, in turn, determines an endogenous city boundary,  $\bar{Z}$ , because for a closed city it must be true that:

$$(5) \quad n = \int_0^{\bar{Z}} \frac{1}{L(z)} dz$$

The usual monocentric city model has an increasing consumption of land the further one lives from the CBD. Consequently, population density, which is the inverse of land consumption decreases.<sup>21</sup> Endogenous rents are also decreasing with distance, to compensate for the increase of the transportation cost. Note that with this pattern of land consumption, Assumption 1 brings variation in scheduling preferences across drivers. Equation (4) links location  $Z_i$  with the marginal utility of being at home  $H_i$ , and hence with the value of travel time  $\alpha_i$  and schedule delay early  $\beta_i$ . Depending on the size of the house, a driver chooses a certain departure time from home and vice versa. The model thus produces endogenous preferences in terms of scheduling (dis)utilities, and hence an endogenous ordering of travelers over time during the peak, and a dynamic equilibrium that accounts for this (endogenous) heterogeneity.

In our model, the arrival time at work  $t_a$ , the location of housing  $Z$ , and the consumption of land  $L$  given  $Z$ , are the three margins of behavior, with the

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<sup>21</sup> Inclusion of the travel related costs (both free-flow travel and congestion costs) into the utility in terms of time in our model is a departure from a standard static monocentric model specification, where pecuniary travel costs enter directly into a budget constraint. Nevertheless, the qualitative results concerning land consumption and the shape of the bid rent curve are the same, as we show later.



rents endogenously determined.<sup>22</sup> A driver  $i$  then maximizes utility  $U$ , which we may rewrite from equation (1) as:

$$(6) \quad U_i = \left( (t_S - T_{FF}Z_i - T_q(t_{ai}) - t_{ai})(w + \varepsilon + \varphi L(Z_i)) + t_{ai}w \right)^b (m - r(Z_i)L(Z_i))^{1-b}$$

### 3.3 Solution of the model

#### 3.3.1 Solution in the nutshell

In our model, both dynamic and spatial equilibria conditions apply, which stipulate that (i) no traveler can gain from unilaterally changing departure time and (ii) utility over space is constant within the city boundaries. In the modeling of endogenous choices of location, land consumption, and arrival times, we consider utility maximization as a sequence of a short-run, a medium-run and a long-run optimization problem. In the short-run equilibrium, in which consumption of land over space and rents are fixed, an individual maximizes utility by choosing the arrival time at work. This short-run setup seems reasonable, as usually travel time adjustments can be made at shorter notice than changes in house size and location. We analytically derive an arrival pattern, and the corresponding generalized congestion cost, that fulfills the dynamic equilibrium condition. It applies given the spatial pattern. In the medium run, assuming fixed rents, but taking into account that the dynamic commuting timing equilibrium will adjust with the spatial pattern, we analytically derive the spatial pattern of land consumption. It satisfies the land market condition, which implies that everything else kept constant, one cannot gain in utility by changing land consumption. Finally, to determine a full long-run equilibrium, we compute rents that satisfy the spatial equilibrium condition, given the assumed land consumption consistent with that rent, and given a corresponding short-run equilibrium arrival pattern.

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<sup>22</sup> To maintain the focus of the paper on the relationship between time allocation versus spatial behavior we keep (implicit) wages fixed and homogeneous across households, in order to prevent too many factors affecting the equilibrium. We also abstain from formally treating employment locations endogenously to keep the model tractable. Introducing the assumption of an open city, in which the utility level is determined exogenously by some given inter-urban level, would most likely enforce our finding that road pricing can increase city size: the higher utility level before immigration has occurred will attract additional inhabitants. Introducing multiple bottlenecks in the city, or treating the CBD as a continuous space, most probably will not change the qualitative results of the model.

This defines the full equilibrium in an analytical sense. To compute it numerically, we make the same steps, but then plug in these rents into an optimal land consumption function, as defined by the medium-run solution, which, in turn, affects the equilibrium arrival pattern. The long-run equilibrium is then found numerically by repeatedly substituting the spatial pattern of land consumption, and computing the arrivals and rents, until convergence is reached. The convergence criterion is the equality of the initially assumed city population to the overall number of inhabitants living within the endogenously defined city boundaries, as calculated by the spatial integral of the population density over the entire city, where population density is the inverse of a land consumption. As an ultimate check of reaching an equilibrium, we compute equilibrium utility levels over space, to confirm that these are constant over space within the city.

### 3.3.2 Short-run equilibrium

In the short-run equilibrium, the arrival times at work are determined. Consumption of land and rents are fixed, meaning that non-time component of the utility function is unaffected by changes in times of arrival. For a person to be indifferent for a marginal change in arrival time  $t_a$ , we must have that at the moment of arriving,  $\frac{\partial X}{\partial t_a} = 0$ . From equation (6) it follows that:

$$(7) \quad \frac{\partial X}{\partial t_a} = -\frac{\partial T_q}{\partial t_a}(w + \varepsilon + \varphi L) - (w + \varepsilon + \varphi L) + w = 0$$

From (7), we derive the time derivative of the equilibrium travel delays as:

$$(8) \quad \frac{\partial T_q}{\partial t_a} = \frac{\varepsilon + \varphi L}{w + \varepsilon + \varphi L}$$

Equation (8) has a close correspondence with the conventional equilibrium in the standard bottleneck model, where the growth rate of travel delays during early arrivals at work is  $\frac{\beta}{\alpha}$ . But an important difference is that in our model, the growth rate of travel delays is not constant, as  $L$  varies across drivers.

It is easy to show that with heterogeneous preferences, the equilibrium queue growth rate cannot decrease over time during the period of early arrivals (e.g., Small and Verhoef, 2007, p. 132). We can interpret equation (8) as the slope of an isocost line for individuals traveling at that instant. Drivers with

heterogeneous values of travel time and scheduling delays would then arrive at the moments which bring them to the lowest achievable isocost level, implying that the queuing cost as a function of arrival time should be tangent to (8) for that individual. The queuing time function  $T_q(t_a)$  should then be convex (meaning a non-decreasing queue growth rate), to make sure that drivers are unable to achieve a lower cost level by rescheduling.

It thus follows from equation (8), that arrivals at work will be in order of increasing land consumption, and that the equilibrium growth rate of the queue rises with house size. Because of this heterogeneity of drivers, the waiting time for the driver with the largest house, is shorter than it would have been if the queue would have grown at her equilibrium rate throughout the peak, i.e., without heterogeneity. The convexity of the curve describing queuing delay by moment of arrival secures that such a benefit from heterogeneity is enjoyed by every traveler except for the very first one, and increases with the moment of arrival.

The “first-in first-out” queuing discipline then implies the same ordering of arrivals at the back of the queue. The order of departure from home, however, also depends on the free-flow travel time.

With the order of passing the bottleneck determined, we can express the generalized congestion cost (including travel delay cost and schedule delay cost, but excluding free-flow travel time cost) in a way similar to van den Berg and Verhoef (2011). To this end, observe that the peak period starts at  $\frac{n}{s}$ , and that in case of homogeneous drivers with identical scheduling preferences, the average (per user) congestion cost would be equal to  $\frac{n}{s}(\varepsilon + \varphi L)$ . This corresponds to the generalized congestion cost from the standard bottleneck model with early arrivals only,  $\frac{n}{s}\beta$ . Equation (9) defines a short-run equilibrium congestion cost  $C_i$  for a driver  $i$  when drivers have heterogeneous scheduling preferences (in particular when these preferences depend on the amount of land consumed,  $L_i$ ):

$$(9) \quad C_i = \frac{\theta_i}{s}(\varepsilon + \varphi L_i)$$

where  $\theta_i$  is the (weighted) number of drivers that would bring a driver  $i$  at the same isocost level as where she is now, if all these  $\theta_i$  other drivers had the same scheduling preferences as driver  $i$  has herself. The factor  $\theta_i$  thus depends on the

convexity of the queuing time function at moments before individual  $i$  arrives. We can therefore express  $\theta_i$  as a function of land consumption:

$$(10) \quad \theta(L_i) = \int_{\underline{L}}^{L_i} \frac{w + \varepsilon + \varphi L_i}{\varepsilon + \varphi L_i} \frac{w + \varepsilon + \varphi l}{\varepsilon + \varphi l} \frac{1}{l} dl + \int_{L_i}^{\bar{L}} \frac{1}{l} dl$$

where  $\underline{L}$  and  $\bar{L}$  are the minimum and maximum levels of land consumption within the city. Equation (10) shows that a driver who arrives closer to  $t^*$  gains most from heterogeneity in scheduling preferences. The reason is that due to the convexity of the travel delay function  $T_q(t_a)$ , the negative congestion externality that earlier drivers impose on her is smaller than the negative externality that would result from drivers with the same scheduling preferences as she has (and who would therefore make the travel delay function linear).

Given the short-run trip timing equilibrium, we can rewrite equation (2) as follows:

$$(11) \quad X_i = (t_S - T_{FF}Z_i)(w + \varepsilon + \varphi L_i) - \frac{\theta(L_i)}{s}(\varepsilon + \varphi L_i)$$

The first term on the right hand side of equation (11) is equal to an “ideal” utility level, which a driver would reach over the course of the morning, had she arrived at the CBD at time  $t^*$  without having faced any traffic jam. The second term is the congestion cost, given the trip timing equilibrium just described.

### 3.3.3 Medium-run equilibrium

The computation of the medium-run problem involves the problem where inhabitants maximize utility by adjusting land consumption at their locations, taking as given the pattern of land rent, the prices and accounting for the effect of land use on trip timing. We assume that the equilibrium congestion cost derived from the short-run equilibrium problem holds, but we now treat  $L$  as a variable argument in that function, to reflect that individuals know that they will adjust travel moments when adjusting land consumption. Then, we can specify the utility function and a budget constraint as follows:

$$(12) \quad U_i = \left( (t_S - T_{FF}Z_i)(w + \varepsilon + \varphi L_i) - \frac{\theta(L_i)}{s}(\varepsilon + \varphi L_i) \right)^b Q_i^{1-b}$$

$$(13) \quad m = Q + r_i L_i$$

We maximize utility by defining the Lagrangian and solving the usual first-order conditions. After solving for the optimum land consumption, we get:

$$(14) \quad L_i = \frac{(b-1)(\theta\varepsilon - s(t_S - T_{FF}Z_i)(w + \varepsilon))}{\varphi(\theta - s(t_S - T_{FF}Z_i))} + \frac{bm}{r_i}$$

Note that when congestion costs are zero, i.e.,  $\theta = 0$  (which would correspond to a model with space-varying free-flow travel time, but without a bottleneck), the optimal consumption of land would be:

$$(15) \quad L_i = \frac{(b-1)(w + \varepsilon)}{\varphi} + \frac{bm}{r_i}$$

The second term on the right hand side of both equations (14) and (15) is the regular conditional demand for land, for a standard Cobb-Douglas utility specification in a static monocentric city model. The first term on the right hand side of equation (15) is a negative correction term, which accounts for the fact that not all utility from being at home comes from the size of the house, as equation (4) shows. The stronger the size effect is (a small  $(w + \varepsilon)/\varphi$  ratio), the smaller (in absolute terms) the term is. But, if the size of the house adds little to utility of being at home, the term gets larger (in absolute terms), and  $L$  is eventually bounded by the non-negativity constraint.

The negative correction term in equation (14) differs from that of equation (15) because in our model, some part of utility from housing is forgone due to the congestion. That is, housing now yields lower utility than with free-flow travel time only, because a driver spends time in a queue and/or early at work, instead of spending that time at home. It is easy to show that the correction term is, not surprisingly, larger (in absolute terms) when congestion is stronger, resulting in a weaker demand for land.

### 3.3.4 Long-run equilibrium

With the long-run equilibrium, we refer to the complete solution of the model in which land rents have adjusted over space in such a way that in the resulting medium- and short-term equilibrium, utility is constant over space within the city. We use numerical methods to compute this long-run equilibrium, as an insightful analytical solution seems unattainable.

We restrict attention to the empirically relevant case where land consumption increases with distance from the CBD. Indeed, it is conceivable that the model might support also the opposite spatial pattern of land consumption, where land consumption decreases with distance, if those who live closest to the CBD are the last to depart from home in the morning and therefore consume more housing than those near the fringe. But we do not consider this potential type of equilibrium worthwhile for further exploration.

### 3.3.5 Calibration

For the calibration purposes we define the model's parameter values such that these values and the resulting equilibrium reproduce a stylized representation of a city with bottleneck congestion in reality. Specifically, in line with the assumption of no late arrivals, we define a morning period that lasts from 6:00 am until 9:00 am. We set this morning period to be equal to 180 units of time, i.e.,  $t_S = 180$ , where one unit of time is 1 minute. The free-flow travel speed is equal to 60 km/h (app. 37 mph). We define one unit of distance as 1 meter; which implies that the free-flow travel time needed to cover 1 meter is 0.001 minute, i.e.,  $T_{FF} = 0.001$ . In equilibrium, the city fringe is located around 65 kilometers away from the CBD; thus, one might think of our calibration representing a typical (American) large urban area. The number of drivers in the city is 6000, i.e.,  $n = 6000$  and the capacity of the bottleneck is 100 cars per minute, i.e.,  $s = 100$ , implying that the peak-period lasts for 60 minutes. The implied 6000 cars per hour would more or less correspond to a 3 lane highway in reality. The exponent for ordinary goods in the Cobb-Douglas utility function is  $\frac{2}{3}$ , implying  $b = \frac{1}{3}$ ; and the daily wage is 100 EUR, i.e.,  $m = 100$ , which corresponds to a monthly net wage of 2000 EUR. Agricultural rent is 1 EUR. As we will find later, in equilibrium an aggregate share of income spent on housing is around 20%, which seems reasonably close to the values observed in reality. The marginal utility of being at work before  $t^*$  is 0.05 EUR, i.e.,  $w = 0.05$ . The parameter that keeps marginal utility of being at home above  $w$  is 0.01 EUR, i.e.,  $\varepsilon = 0.01$ ; the parameter that "converts" the amount of consumed land into marginal utility of being at home is equal to 0.008, i.e.,  $\varphi = 0.008$ . These parameter values were chosen such that they yield what we believe are reasonable equilibrium outcomes. For instance, empirical values for the scheduling parameters suggest that their relative values approximately satisfy

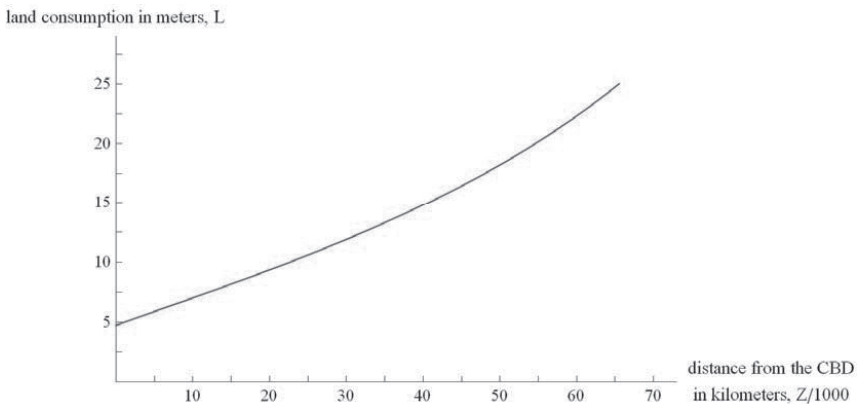
$\gamma = 2\alpha = 4\beta$  (see Small, 1982).<sup>23</sup> While our model results in a distribution of marginal utility values of being at home, we try to stay around that ratio for the averages. In an endogenously determined time interval from 7:16 am until 9:00 am there is at least some traveling. During other earlier times in the morning, everyone is at home. Later, we check the robustness of the main results by means of sensitivity analyses.

3.4 Unpriced market equilibrium

Figures 3.3 – 3.5 show equilibrium base case patterns of, respectively, land consumption, population density and rents over space, for the base calibration of the numerical model. The upward sloping consumption of land function, and downward sloping rent function, are of course consistent with patterns usually found for the static monocentric city models, and empirically (e.g., Glaeser, 2008).

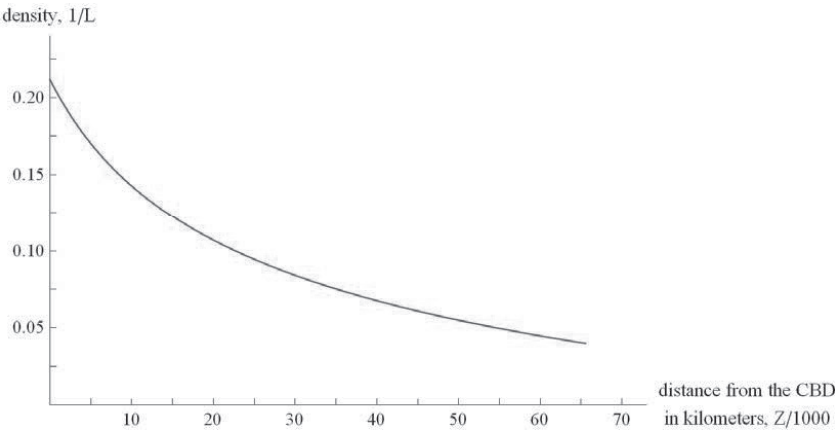
Figure 3.6 shows the dynamic equilibrium travel time patterns by residential location. The morning commute in our base case is as follows. Although arriving last, just before  $t^*$ , the inhabitant who lives at the city fringe

Figure 3.3. Consumption of land by residential location (base equilibrium)

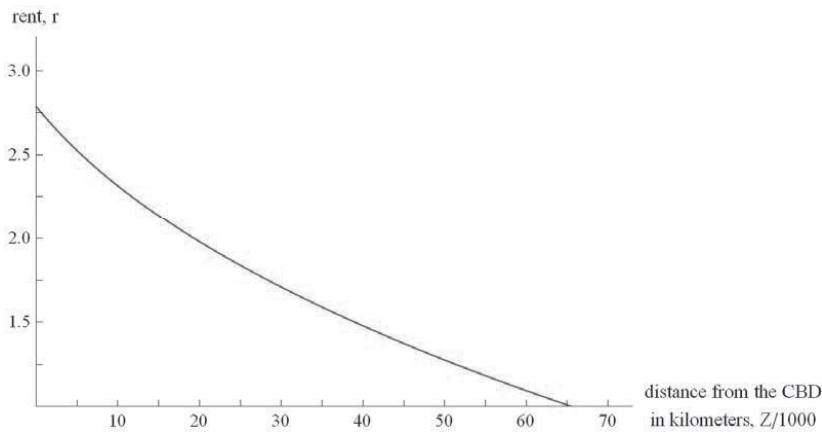


<sup>23</sup> The daily wage of 100 EUR translates into an hourly wage of 12.5 EUR, which, in turn, yields approximately 0.2 EUR and 0.05 EUR per minute at work after and before  $t^*$ .

**Figure 3.4.** Population density by residential location (base equilibrium)



**Figure 3.5.** Rents by residential location (base equilibrium)

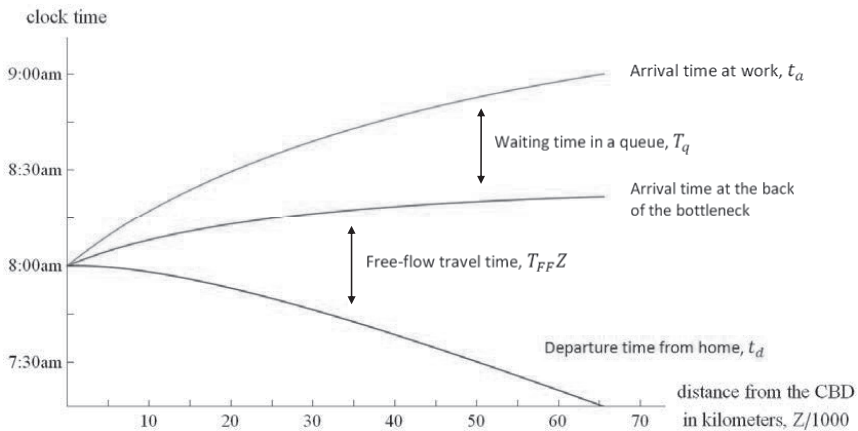


is the first to depart from home. With the progress of clock time, drivers depart from home in order of decreasing distance from the city fringe. This dynamic pattern of departure moments depends on the free-flow travel speed with which drivers cover the distance between their residence and the CBD, as in a market equilibrium they pass the bottleneck in order of the relative size of their houses. That is, the driver with the smallest house (living right next to the CBD)



is the first to pass the bottleneck, and the one with the largest house (at the fringe) is the last one. All drivers, except the first to pass the bottleneck, incur some positive waiting time. This travel delay is reflected in Figure 3.6 by the difference between times of arrival at the back of the queue, and at work. The travel delay grows monotonically during the peak, reaching a maximum for the last arrival, at  $t^*$ . We assume that the entire morning lasts 180 minutes, and our model results in an endogenous period of 104 minutes (1 h 44 m) when at least someone in the city is traveling, i.e., during the other 76 minutes (from 6:00 am until 7:16 am) everyone is at home. The traffic jam itself lasts 60 minutes, as  $n/s=60$ . The endogenous city boundary is at 65.53 km.

**Figure 3.6.** Travel patterns by residential location in an unpriced market equilibrium (base equilibrium)



### 3.5 City with first-best road pricing

#### 3.5.1 Model with road pricing

The literature on the standard Vickrey dynamic bottleneck model shows that waiting time in a queue, and thus waiting time costs  $\alpha T_q$ , is a pure loss, that is fully eliminated by a first-best time-dependent road toll. In the case of homogeneous drivers, this is achieved by substituting (at each moment of arrival) the waiting time cost from the unpriced market equilibrium with an equally large road toll (see, e.g., Vickrey, 1969; Arnott et al., 1993). Thus, the generalized travel price stays the same as in a no-toll equilibrium. However,

from the social point of view a road toll, unlike travel delay, is not a cost incurred by the society, but a welfare neutral monetary transfer from the drivers to the government. Thus, road pricing reduces an overall welfare loss due to travel delay cost (with schedule delay cost still present). The schedule delay cost remains in the optimum, and it is not affected by road pricing if drivers are homogeneous. Arnott et al. (1993) offer further discussion of this standard Vickrey's model with pricing.

We are interested in how the results of our spatial model change under first-best road pricing, compared to the no-toll equilibrium outcomes. To this end, we repeat the analysis presented above while accounting for first-best time-dependent toll  $\tau(t_a)$ . The setup of the model slightly changes, as the drivers under first-best road pricing no longer face waiting time, i.e.,  $T_q = 0$ , so the time of arrival at the back of the bottleneck is identical to the time of arrival at work. We can rewrite the utility function from equation (6) and the budget constraint from equation (3) as follows to account for pricing:

$$(16) \quad U_i = ((t_s - T_{FF}Z_i)(w + \varepsilon + \varphi L_i) - t_{ai}(\varphi L_i + \varepsilon))^b Q_i^{1-b}$$

$$(17) \quad m + \chi = Q_i + r(Z_i)L_i + \tau(t_{ai})$$

where  $\chi$  represents a lump-sum monetary transfer from the government back to the drivers, which is the average (per driver) of the total road toll revenues.

As in the no-toll setting, location, land consumption, rents and arrival times at work are endogenous; and so is the road toll. The equilibrium road toll should secure that the dynamic equilibrium condition that no driver should have an incentive to unilaterally change her departure time is satisfied in the situation where no queue emerges and the bottleneck operates at full capacity throughout the peak period. Since there is no waiting time, the departure times from home are then easily found by subtracting the free-flow travel times from the arrival times at work.<sup>24</sup>

### 3.5.2 Solution of the model with road pricing

For the solution, we again distinguish between a short, a medium and a long-run optimization problem. In the short run, in which a driver chooses time of

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<sup>24</sup> A road toll might also account for other types of negative externalities, such as environmental costs which are influenced also by the overall distance traveled. To maintain focus in this paper, we consider only congestion costs.

arrival at work while keeping everything else constant, we determine the optimal toll  $\tau(t_a)$  that achieves that the dynamic equilibrium condition is satisfied under the no-queue constraint. In contrast to the no-toll case, a change in the time of arrival now affects the monetary component of the utility function, as different moments of arrival correspond to different road tolls, and hence to different remaining (after-toll) budgets. An equilibrium road toll reflects the trade-off that individuals make between the opportunity cost of an early arrival versus the money one has to pay, and therewith, the forgone consumption of the numeraire good – as the consumption of land is fixed in the short-run. We can rewrite the necessary marginal condition for an individual's optimized arrival time as follows:

$$(18) \quad \frac{\partial U}{\partial t_a} = - \frac{\partial U}{\partial Q} \frac{\partial Q}{\partial t_a}$$

Since the price of a numeraire good is 1,  $\frac{\partial Q}{\partial t_a}$  directly shows the equilibrium shadow price of a marginal change in arrival time in terms of the implied foregone consumption of the numeraire good, as the budget constraint (17) implies:

$$(19) \quad \frac{\partial \tau}{\partial t_a} = - \frac{\partial Q}{\partial t_a}$$

Applying equilibrium condition (18) and substituting (16) into it leads to the following condition on the slope of the toll schedule at the moment of traveling:

$$(20) \quad \frac{\partial \tau}{\partial t_a} = (\varepsilon + \varphi L) \frac{b}{(1-b)} \frac{Q}{X}$$

In the standard bottleneck model with homogeneous drivers, the growth rate of the optimal toll for each arrival is  $\beta$ , which has the equivalent of  $H - w = \varepsilon + \varphi L$  in our model. Intuitively, for each minute of arriving closer to the preferred arrival time  $t^*$ , the scheduling cost decreases by  $\beta$ , so to keep the generalized cost constant over the peak period (as required in the dynamic equilibrium) without queuing, that utility gain is compensated for by an equally large increase in the monetary toll. Our result differs because, unlike in the spaceless basic bottleneck model, in a monocentric city the marginal utility of income varies over space when the income elasticity of land demand is non-zero, as shown, for example, by Mirrlees (1972) and Wildasin (1986). The closer

to  $t^*$  a driver arrives at work, the more toll she has to pay and thus the more valuable money is. The optimal toll schedule implied by (20) accounts for this.

Analogous to the no-toll scenario, a toll function  $\tau(t_a)$  should be convex to support an equilibrium under heterogeneous scheduling preferences. This is achieved if the drivers arrive at the CBD in order of increasing land consumption, as in the no-toll case. Given this order of arrival, we may rewrite equations (9) and (10) and derive the first-best generalized price for road use  $C_i^{FB}$ :

$$(21) \quad C_i^{FB} = \frac{\theta_i^{FB}}{s} (\varepsilon + \varphi L_i) \frac{b}{(1-b)} \frac{Q}{X}$$

where  $\theta_i^{FB}$  is defined in a similar way as  $\theta_i$  was in the no-toll equilibrium. Following van den Berg and Verhoef (2011),  $\theta_i^{FB}$  is:

$$(22) \quad \theta_i^{FB} = \int_{\underline{L}}^{L_i} \left( (\varepsilon + \varphi l) \frac{b}{(1-b)} \frac{Q(l)}{X(l)} \right) / \left( (\varepsilon + \varphi L) \frac{b}{(1-b)} \frac{Q(L)}{X(L)} \right) \frac{1}{l} dl + \int_{L_i}^{\bar{L}} \frac{1}{l} dl$$

We apply a geometric argument and derive the optimal road toll<sup>25</sup>:

$$(23) \quad \tau_i = \left( \frac{\theta_i^{FB}}{s} - t_a \right) (\varepsilon + \varphi L) \frac{b}{(1-b)} \frac{Q}{X}$$

The lump-sum transfer from the government to the drivers is then the average (per driver) of the overall toll revenues collected:

$$(24) \quad \chi = \frac{1}{n} \int_0^{\bar{z}} \frac{\tau}{L(z)} dz$$

In the medium-run we solve for the optimal land consumption, while taking rents and location as given, but accounting for the effect that the size of one's house will affect one's position in the order of passing the bottleneck. That is, the larger the house, *ceteris paribus*, the closer to the preferred arrival time one will reach the CBD in the short-run equilibrium. We specify a Lagrangian using equations (16) and (17). Solving the first-order conditions, we get closed-

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<sup>25</sup> The road toll at each moment of arrival can be found by multiplying the slope of the isocost function as given in (20) by the base (shown in the left bracket of (23)) which is the time difference between given arrival time and the start of the peak period, if all drivers would have the same scheduling preferences as an individual who arrives at the given moment.

form solutions for the optimal consumption of land  $L^*(r(Z), Z)$  and numeraire good  $Q^*(r(Z), Z)$ .

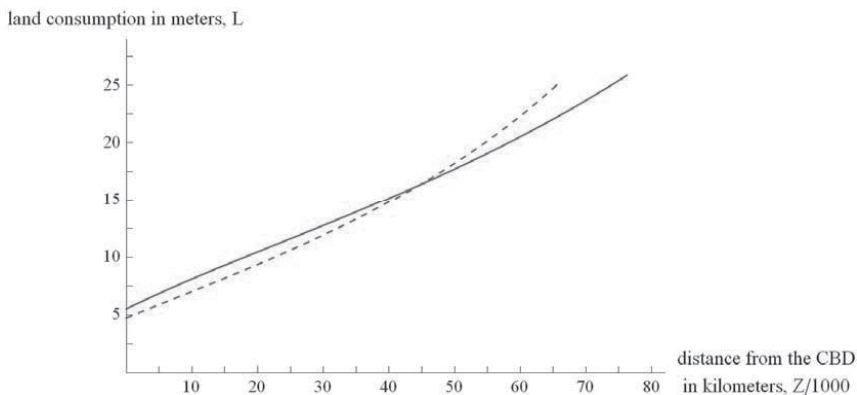
In the long-run equilibrium, in which the equilibrium rents are determined, we follow the heuristic numerical procedure as described for the no-toll case. Again, we only consider the empirically relevant case of  $\frac{\partial L}{\partial Z} > 0$ .

3.5.3 Equilibrium with road pricing

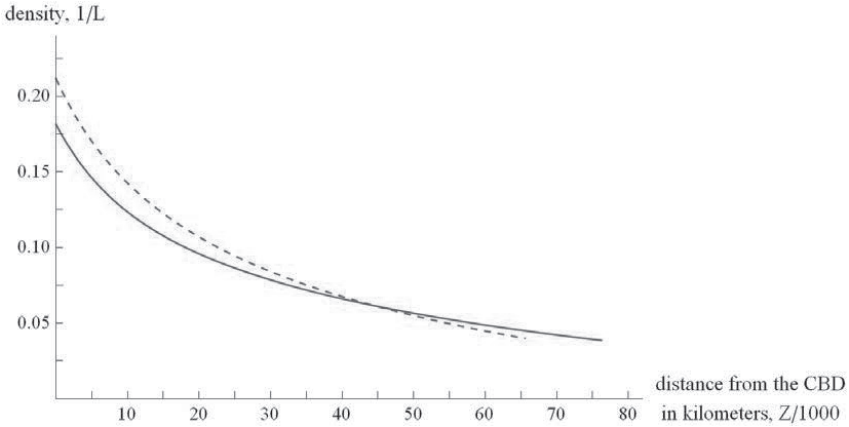
Figures 3.7 – 3.9 show (with solid lines) the spatial patterns of land consumption, population density and rents for the reported calibration parameters, when the first-best time-dependent road toll is levied in the monocentric city. For comparison, the dashed lines show the corresponding spatial patterns in the no-toll market equilibrium. Figure 3.10 shows the first-best road toll plotted against the location within the city, as each particular location corresponds to a certain arrival time. The lump-sum transfer from government is 5.41 EUR. The increase in utility from road pricing corresponds to one that would be achieved by an exogenous increase in wage by 4%.

Arguably, the most striking result of an introduction of road pricing in the model is the increased demand for land: the city boundary moves from 65 km (a no-toll case) to 76 km (under road pricing). This result holds even though higher land-rents are assumed to flow out to an absentee landlord and also

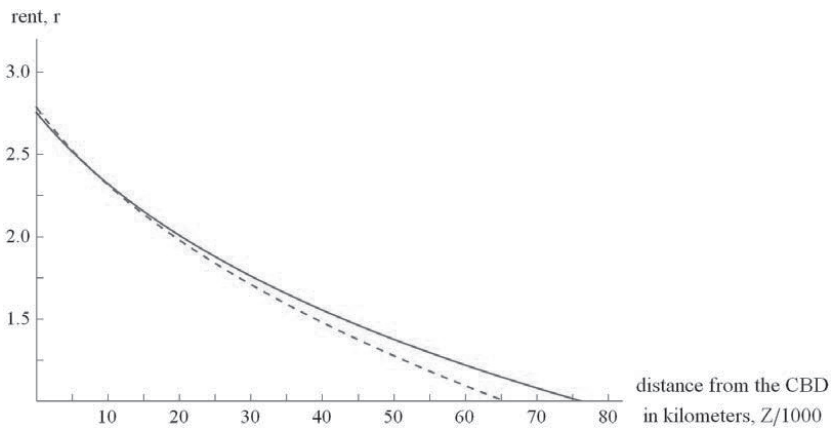
**Figure 3.7.** Consumption of land by residential location [with pricing (solid) and without (dashed)]



**Figure 3.8.** Population density by residential location [with pricing (solid) and without (dashed)]



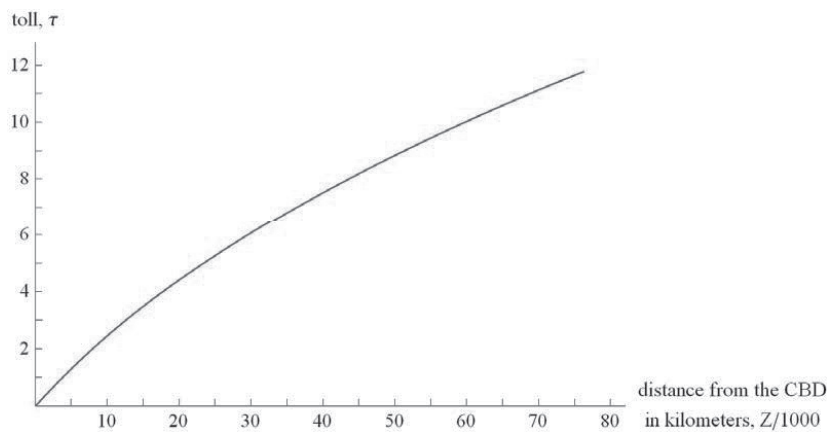
**Figure 3.9.** Rents by residential location [with pricing (solid) and without (dashed)]



when the lump-sum transfer from toll revenue is not redistributed back to the city inhabitants; although the extent of urban sprawl is then less pronounced.<sup>26</sup> Moreover, the result obtains even though land rents have increased which in

<sup>26</sup> The city size is 73 km when road tolls are not redistributed back to the inhabitants.

Figure 3.10. Road toll by residential location

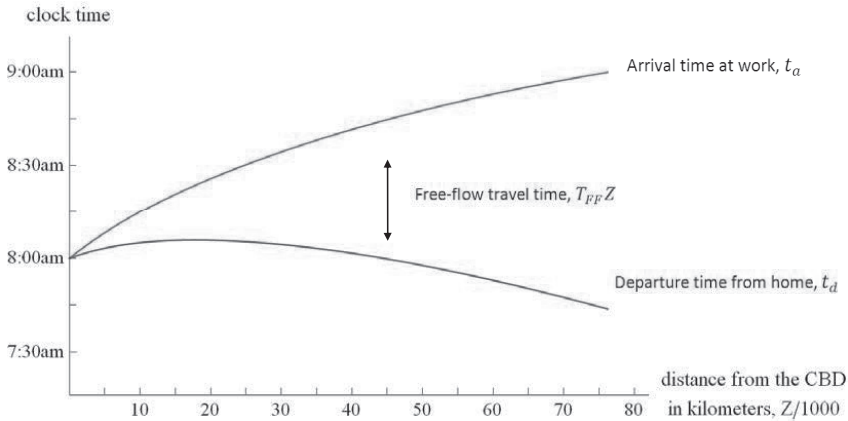


itself would lead to a reduction, not increase, in land consumption. Without this increase, the expansion would of course have been even bigger. This all is in contrast with the usual results of urban models with static congestion, which predict cities to become denser with road pricing.

This contrast stems from two factors. First, the assumed relationship between the size of the house and the marginal utility of spending time in it induces drivers who spent more time at home under road pricing to invest in larger housing. Changes in scheduling behavior can be observed by comparing Figure 3.6 with Figure 3.11, which shows that the new dynamic equilibrium travel patterns are such that all inhabitants, except the one who arrives first at work, depart from home later under optimal road pricing than in the unpriced market equilibrium, and thus spend more time at home. The peak period lasts for 1 h, and the period of when at least someone is on the road lasts for 1 h 16 m (i.e., during the other 1 h 44 m everyone is at home).

In principle, in a static model the same effect could be captured in a more ad hoc fashion if it were assumed that time gain from road pricing are partly spent at home, and therefore lead to an increase in the marginal utility of floor space. As departure time decisions are crucial in this respect, it seems strongly preferable not to follow such an ad hoc formulation but rather to have a dynamic perspective with endogenized departure times.

**Figure 3.11.** Travel patterns by residential location with the first-best road pricing



The second factor is the difference between the assumed congestion technologies in our model versus the standard monocentric model. We employ bottleneck congestion, the standard formulation of which implies that road pricing does not directly affect the marginal cost of traveling one additional unit of distance from the CBD, as travel towards the bottleneck occurs at free-flow speeds both with and without road pricing. Travelers pay a road toll at the bottleneck irrespective of the free-flow distance they cover. Road pricing with static flow congestion, on the other hand, implies that each unit of distance is taxed, raising the generalized prices per unit of distance, thus creating an incentive for the drivers to live closer to the CBD. An absence of the latter mechanism contributes to our urban sprawl result.

Note that the model specification is set such that it represents the effect of dynamic road pricing on the demand for land in the most articulated fashion. In reality, utility from housing need not be linked exclusively to the time spent at home. One may expect the city to expand to a smaller extent if the value from a house is partly independent of time spent in it.<sup>27</sup> However, the mechanism discussed in the chapter would remain relevant; the exact extent of the effect is an empirical question.

<sup>27</sup> We have verified that by including in the utility function in equation (2) a time-invariant component which is positively related to land consumed but does not depend on the amount of time spent at home. As expected, the more important this part of the utility becomes, the less pronounced is the effect of road pricing on the demand for land.



### 3.6 Sensitivity analysis and other policies

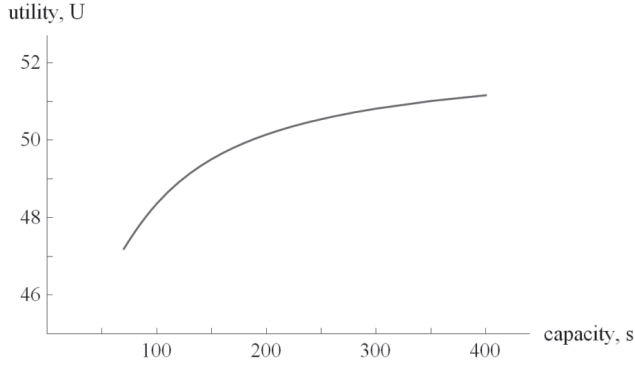
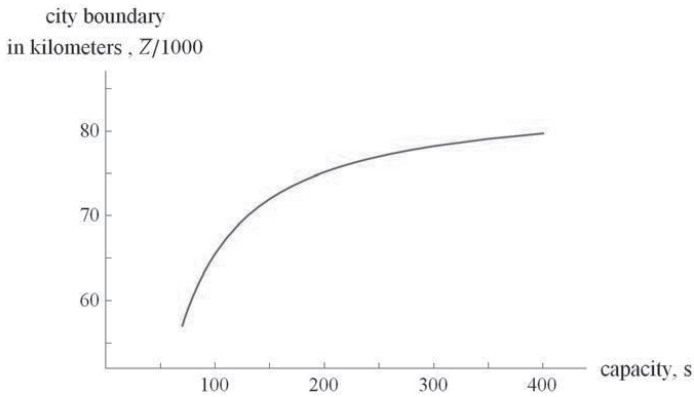
#### 3.6.1 Alternative policy measures

Both land consumption and the utility level of inhabitants increase when first-best time-dependent road pricing eliminates queuing delays in the city. While a road tolling is a potentially Pareto-improving policy, the scarcity of real-life congestion pricing schemes signifies how technically and politically challenging the implementation of road pricing is (in part, due to the redistribution effects). Noticeable exceptions are congestion charges in London, Singapore, Stockholm, and on some highways in the USA. Alternative policy instruments to improve traffic conditions have been proposed in the literature, and for some of them our model can provide an assessment of their spatial and welfare effects as well. These policies include bottleneck capacity expansion, a change of the transportation technology, and the promotion of working from home. In our model, these policies might be represented with the changes of parameter values  $s$ ,  $T_{FF}$  and  $\varphi$ . For the sensitivity analysis, we focus on these parameters, with a clear policy interpretation. We do not believe that there are other parameters of sufficient interest for a sensitivity analysis.

#### 3.6.2 Bottleneck capacity ( $s$ )

Arguably, the most widespread policy response to alleviate congestion is to construct additional road capacity. In our model, we can analyze the role of capacity by varying the value of the parameter  $s$ , the capacity of the bottleneck. Figure 3.12 illustrates the effect of the capacity change on utility level in the city. The curve in Figure 3.12 is concave because a variation of  $s$  at lower levels changes peak duration, and therewith utility, to a greater extent than does the further expansion of an already large capacity. Expectedly, the utility increases in the city as the capacity is increased, because the time period of waiting in a car at each moment of arrival decreases, and because we do not consider any cost of capacity. Figure 3.13 shows that land at greater distance becomes inhabited as the capacity of the bottleneck is increased.

The rent curve, not shown, becomes less steep if the capacity increases. Intuitively, the relative benefit of being close to the CBD reduces when queuing becomes less serious, as especially the more distant residents face the longest queues, and hence benefit more from a higher capacity.

**Figure 3.12.** Utility for various bottleneck capacity levels**Figure 3.13.** City size for various bottleneck capacity levels

We also considered a case when the capacity level approached infinity. That case corresponds to a monocentric city model without congestion. All drivers then arrive at the CBD exactly at the preferred arrival time  $t^*$ , and the departure moments are  $t_d = T_{FF}Z$ . The resulting utility level in the city without congestion is 59.77 and the city fringe is located 111 km away from the CBD; these are the asymptotes in Figures 3.12 and 3.13.

### 3.6.3 Free-flow speed ( $T_{FF}$ )

Another parameter of interest would be the free-flow speed, increases of which would lower the parameter value  $T_{FF}$ . Some locations that are initially outside the city will become resided when  $T_{FF}$  falls, because commuting time from those locations is no longer prohibitively high. A higher free-flow speed results in our model in larger land consumption, and a higher utility throughout the city. These effects are in line with those observed empirically after improvements in transport, such as the invention of a car (see, for example, Glaeser and Kahn, 2004), and also with predictions from the monocentric model with static congestion.

### 3.6.4 Lot size effect of the marginal utility of spending an additional time at home ( $\varphi$ )

The parameter  $\varphi$  relates residential land consumption to the marginal utility of spending an additional unit of time at home. Changes in  $\varphi$  might come through changes, among others, in idiosyncratic preferences for spending time at home due to, for example, a marriage (de Palma et al., 2014), the birth of a child, a life style, or the presence of local amenities. From the policy point of view, (part-day) teleworking could be seen as a measure that might influence  $\varphi$  (Gubins and Verhoef, 2011). We interpret teleworking as an out-of-office work arrangement, where an employee can perform some work tasks from home. This possibility would affect utility of being at home.

An increase in  $\varphi$  leads to a lower density and higher rents, because land yields higher utility per unit of time and per unit of income, and thus induces people to consume more land. That leads to a higher utility level in the city, but the congestion cost becomes larger as well. A steeper travel delay function is required for equilibrium when  $\varphi$  becomes higher and being at home is valued more. Waiting time therefore increases for each moment of arrival, implying a more severe traffic jam. The result of the increase in city size due to road pricing remains present and of the same relative order if the level of  $\varphi$  is varied. This was confirmed by numerical analysis not included in this chapter.

## 3.7 Summary and conclusions

We analyzed road congestion in a city where both residential locational choice, and the choice of the time of departure from home to a workplace in the

morning, are the results of optimizing behavior. We show that this setup yields results that are in sharp contrast to those from the more conventional modeling approach of assuming static flow congestion. One of the main results is that there will be a decrease in the population density in a city, and an increase in city size, with first-best time-dependent road pricing, even when the collected road toll revenues are not redistributed back to the city inhabitants. Effectively, road pricing may thus lead to urban sprawl.

The driving force behind our results is an assumption that relates the choice of house size to the choice of the time of departure. An individual who lives in a large house is assumed to value additional time spent in it at a higher rate than someone who lives in a smaller house. This assumption is justified with (i) the empirical evidence from hedonic price studies, which indicate a positive effect of a lot size on utility and (ii) the reasonable observation that, among other channels via which one might derive utility from housing, at least some part of that utility should depend on the amount of time an individual spends in it. We show that drivers in equilibrium pass the bottleneck in order of increasing house size. In a monocentric city, the smallest houses are located close to the CBD, so drivers who live closest to the CBD are the first to arrive at work.

The introduction of first-best time-dependent road pricing eliminates queuing, as it does in the non-spatial bottleneck model. It substitutes waiting time costs for a welfare neutral monetary transfer from the drivers to government. The first driver to arrive at work pays no toll, but drivers who arrive closer to the preferred time of arrival pay tolls that counterbalance the lower scheduling cost they face. Unlike in the standard bottleneck model, the change in toll reflects differences in the marginal utility of income. We account for this in our optimal toll function. As in the no-toll case, individuals account for the effect of house size on the generalized travel cost. The long-run rents, which we numerically compute, are such that the spatial equilibrium condition is fulfilled. Finally, we determine location specific travel patterns within the city based on the equilibrium land consumption function.

Optimal road pricing induces people to consume more land, as housing yields larger benefits because people depart later and thus spend more time at home. As a result, the city territory grows. Similar effects apply when the bottleneck capacity expands, or when the free-flow speed increases. In effect,

this reflects a result that is familiar in the literature, namely, that a better transportation technology causes urban sprawl.

Our study thus implies that the relation between road pricing and city density needs not be as straightforward as suggested by the conventional monocentric model with static congestion. All that is “needed”, in terms of assumptions, to achieve this, is that spending more time at home provides a greater incentive to use more space. This basic mechanism, represented in an admittedly stylized manner in our model, seems rather plausible. One of the consequences for transportation policy might be that if some externalities – such as pollution – increase with driving distance, the interaction between congestion pricing and this other externality may turn from favorable – in the static model – to a real trade-off – in a dynamic setting.

## 4 Welfare effects of road pricing and traffic information under alternative ownership regimes

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### 4.1 Introduction<sup>28</sup>

Unpredictable stochastic variation in product quality is common in many markets. The transportation market is a case in point: car accidents that block the street, bridge openings, or weather conditions might slow down traffic in an unpredictable way. Information and telecommunication technologies (hereafter, ICT) can then potentially support drivers with more reliable data on the duration of travel before the decision to make the trip is made.

We study the social welfare effects of the provision of information about product quality in the context of road transportation. Specifically, we show how the strategic behavior of market agents, for different market ownership regimes, affects social welfare. We consider a game-theoretical setup of the market where a road operator, an information provider, and atomistic end users interact. The information provider reports the actual realization of the time necessary to make the trip. Conditional on the prices for road use and information, the consumers decide whether to travel, and whether to purchase information. We assess public versus private information provision, as well as collusion of road and information providers, by analyzing nine market forms with different ownership regimes, and compare the social welfare they generate.

We construct a simple model with elastic travel demand and stochastic user costs, and endogenous demand for traffic information. Depending on the price of information, the demand for travel might vary, thus affecting the possible profit and welfare from road operation. In turn, an increase of a road toll forces more consumers to abstain from a trip, and hence limits the demand for information. Therefore, the information price affects the demand for travel and the price of travel affects the demand for information. The identification and welfare analysis of the product/information price interdependence is the main contribution of this chapter.

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<sup>28</sup> This chapter is published in Transportation Research Part A (Gubins et al., 2012).

Markets with limited information have since long been studied by economists (Stiglitz, 2000). The seminal paper by Stigler (1961) is the first attempt to outline the economic reasoning behind information acquisition. He notes that the optimal amount of “search” for the best price might be computed by equating its marginal cost with its marginal benefit. Kihlstrom (1974) looks specifically at the factors behind the demand for information. Salop (1977) and Kehoe (1996) link consumer knowledge about a product to the product price. Emmerink et al. (1998b) explicitly derive the demand for road information from an elastic travel demand. But the markets they model lack a separate, strategically acting information provider.

We follow the approach of Emmerink et al. (1998b) in the set-up of the model, and extend it by considering pricing behavior of the road operator and information provider. In our model we allow for an elastic demand for road use and we track the Nash behavior of market agents. In our model, none of the operators can affect the quality of its own performance, as we restrict our attention to the price dimension only. Thus, the information provider delivers the exact traffic information, while a road operator can not influence the traffic conditions of the road network. Zhang and Verhoef (2006) show the effect of monopolistic traffic information on welfare for a one-link toll-free road network. This chapter, to the best of our knowledge, is the first to consider a multiple-link market with an elastic travel demand, and independent road and information suppliers.

We assume that the road supplier does not adjust the prices depending on the product quality. This is either because the supplier himself is unaware of the precise product quality on a specific day, or it may lack a fine pricing mechanism. This setup suits a road transport market well, as even if a road operator knows the traffic conditions, it might not be able to change a road toll accordingly. Travelers might dislike road toll variations, and to make a road pricing acceptable, the road operator might be constrained to use a fixed toll.<sup>29</sup>

Advanced Traveler Information Systems (hereafter, ATIS) is a concrete example of ICT implementation in transportation. Papers by Emmerink et al.

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<sup>29</sup> More generally, if the price reveals the exact quality, traffic information is relevant only when the road toll is not yet known on the moment the route is chosen, or travelers respond to the expected road price only. Our analysis may be taken to consider an undifferentiated toll, or the expected value of a differentiated toll, the value of which is known by the travelers only after the route is chosen.

(1996b), Verhoef et al. (1996), de Palma and Lindsey (1998), Yang (1999), Zhang and Verhoef (2006), and Fernandez et al. (2009) investigate the effect of free ATIS on the drivers' decision to travel. They appraise efficiency inputs of information when road pricing is or is not in place. These papers allow for negative external effects of individual travel, i.e. congestion. Often, indeed, negative congestion externalities are taken into account in the transportation literature. Given our primary focus on strategic interactions between suppliers, we assume that the road network is uncongestible. Theoretically, both public and private providers internalize the negative externalities into the road toll (Small and Verhoef, 2007). The difference between the pricing rules is that the private provider would impose a demand-related mark-up, which increases if demand becomes less elastic. By setting the external marginal cost to zero, we still preserve the monopolistic mark-up on top of the first-best charge in the model, so the main difference between private and public supply is maintained in our analysis. But a second-best distortion affecting welfare effects is ignored.

Our study is related to the rapidly growing literature on travel time variability. This literature considers, for example, the relation between expected travel times and their variability (Peer et al., 2012); and the valuation of travel time variability (Lam and Small, 2001; Small et al., 2005; Fosgerau and Karlström, 2010; Koster et al., 2011). But in this chapter the value of information arises from the possibility it gives to avoid long travel times, and the value of variability per se does not play a role.

The chapter is organized as follows. Section 4.2 sets up travel demand and costs, and derives from these the demand for traffic information. Section 4.3 shows pricing strategies of a road operator and an information provider under various ownership regimes. Section 4.4 runs numerical analysis to compare welfare outcomes of different market arrangements. Section 4.5 proves the robustness of the results. Section 4.6 concludes.

## 4.2 Model

### 4.2.1 Travel demand and costs

We consider a road network of  $n \geq 2$  parallel routes connecting one origin and one destination. Risk-neutral drivers are willing to make a trip if the benefits of doing so are at least equal to the costs; otherwise they stay at home (or perhaps



use alternative transport not explicitly modeled). For analytical convenience we assume that there is a linear inverse demand function for travel of the form  $D^T = d - aN$ , where  $N$  is the number of drivers. A driver's  $j$  individual travel benefit is thus  $D_j^T = d - aN_j$ , where  $N_j$  is the number of drivers with a higher travel benefit than driver  $j$ . The assumed linear form does not appear to be decisive for the main qualitative results that we will derive below.

The cost of the trip without delays  $C^0$  is constant and includes car depreciation, fuel and time costs. This cost function has several implications. First, there are no externality effects in the network. Second, it implies that we assume that people are homogenous with respect to the value of time. Finally, all used routes should be identical in terms of the expected generalized costs (Wardrop, 1952). This is required for parallel routes to attract travelers both with and without information.

Possible delays due to, for instance, road accidents blocking the way or other incidents, make the travel cost stochastic. With probability  $p$  the cost of the trip on a particular route increases from  $C^0$  to  $C^1$  if a driver uses this route. If one route is blocked, but the driver uses alternative unblocked route, the driver's cost is  $C^0$ . The probability of simultaneous independent incidents occurring on all  $n$  roads is  $p^n$ . Drivers are perfectly aware of the possible cost levels and the probability associated with them, and rationally estimate expected travel cost as  $E(C) = C^0(1 - p) + C^1p$  when being uninformed. An uninformed driver chooses one route before departure.

We assume a binary distribution of travel time, i.e., either  $C^0$  or  $C^1$ . The introduction of additional cost levels, or even a continuous probability density function, does not seem to alter the qualitative nature of the demand function for information, and preserves the main results.

A multiple-route setup allows for a two-faceted benefit that information can bring to informed drivers: the benefit from (i) choosing whether to drive or not, and from (ii) the route choice. Even those drivers who always travel, regardless of information availability, gain from traffic information.

The road operator, which may be either welfare or profit maximizing, controls the whole network and takes its layout as given. Assuming no deterioration of the roads, the operator's marginal cost is zero.

Using this static setup, we will next derive drivers' willingness to pay for information in the next subsection.

#### 4.2.2 Demand for information

Traffic information reveals the realization of the costs of travel. With traffic information, a driver – while still at home – gets access to information and observes the costs of travel on each of the  $n$  routes. Subsequently, the driver chooses whether to travel and if so, which route to take. If at least on one of the routes the cost of travel is lower than the benefit, the driver makes a trip on such a route. If the cost on *all* routes is higher, the driver abstains from a trip. We conveniently assume no incident can happen en route – i.e., all information is accurate. Our key interest in this section lies in how much drivers are willing to pay for such information.

The willingness to pay for information of driver  $j$  (hereafter  $wtp_j^I$ ) is the difference between the expected consumer surpluses for informed and uninformed traveling. When traffic information is not available, driver  $j$  compares the expected cost  $E(C)$  with her benefit of traveling  $D_j^T$ , and then decides whether to travel or not. When information is available, the expected consumer surplus depends on the relative size of the benefit  $D_j^T$  in comparison to costs  $C^0$ ,  $E(C)$  and  $C^1$ , as explained below.<sup>30</sup>

Drivers with demand  $D_j^T \geq C^1$  travel irrespective of information availability. Of course, they prefer to incur the lowest cost possible, so they use information to make a better route choice to avoid delays. When informed, they face a cost  $C^0$  in a fraction  $1 - p^n$  of the cases, compared to a fraction  $1 - p$  when uninformed. Thus, the expected cost of an informed trip is  $(C^0 + \pi)(1 - p^n) + (C^1 + \pi)p^n$ , where  $\pi$  is the price of information. The maximum price that driver  $j$  is willing to pay for information,  $wtp_j^I$ , conditional on her travel benefit  $D_j^T \geq C^1$ , is:

$$(1) \quad wtp_j^I = (C^1 - C^0)(p - p^n)$$

The willingness to pay for information is constant and does not depend on the individual's willingness to pay for travel,  $D_j^T$ . The reason is that the benefit of information in this case is solely a route choice benefit, which is a function of

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<sup>30</sup> One might also consider the cost of uncertainty, i.e. the cost of not knowing what the actual cost of the trip will be. It manifests itself in a psychological discomfort of a drive, in an inability to schedule the agenda properly and so on. The cost of uncertainty only applies to uninformed travelers. For informed drivers the cost of uncertainty is zero. Inclusion of a homogeneous value of uncertainty across persons does not affect the results substantially. For the clarity of exposition we omit it; see for example Emmerink et al. (1998b) and de Palma and Picard (2006).

the cost of a delay,  $C^1 - C^0$ , and the rate at which information helps to avoid this delay,  $p - p^n$ . By default, the expected number of trips is the same both with and without information.

Drivers with demand  $C^1 > D_j^T \geq E(C)$  always make the trip when uninformed, although in a fraction  $p$  of the cases they face a cost  $C^1$ , which is higher than their benefit  $D_j^T$ . Nevertheless, in terms of expected consumer surplus, traveling pays off. With information, drivers abstain in a fraction  $p^n$  of the cases, to avoid unbeneficial trips. The lower the travel benefit, the higher the resulting information benefit is. Thus, besides a route choice benefit, defined by equation (1), there is a participation benefit. A participation benefit is the benefit one gets by changing the decision of whether to make a trip or not. In contrast to the route choice benefit, the participation benefit depends on  $D_j^T$ . The expected consumer surplus is  $(D_j^T - C^0)(1 - p^n) - \pi$ . The willingness to pay for information of driver  $j$ , conditional on demand  $C^1 > D_j^T \geq E(C)$ , is:

$$(2) \quad wtp_j^I = (C^1 - C^0)(p - p^n) + p^n (C^1 - (d - aN_j p^n))$$

For this segment of travel demand,  $wtp_j^I$  is increasing as the marginal benefit of a trip decreases, because the benefit of forgoing the trip at cost  $C^1$  then becomes larger. The expected number of trips for these travelers with information is always lower than without information, because they no longer drive in a fraction  $p^n$  of the cases.

Drivers with demand  $E(C) > D_j^T \geq C^0$  do not travel without information, as the expected cost of travel exceeds the benefit. However, information makes it beneficial to travel in a fraction  $1 - p^n$  of the cases. So,  $wtp_j^I$ , conditional on demand  $E(C) > D_j^T \geq C^0$ , is:

$$(3) \quad wtp_j^I = (1 - p^n)(d - aN_j - C^0)$$

Here  $wtp_j^I$  is decreasing as  $D_j^T$  becomes smaller, because the participation benefit then decreases. The expected number of trips with information is always higher than without information (when it is zero).

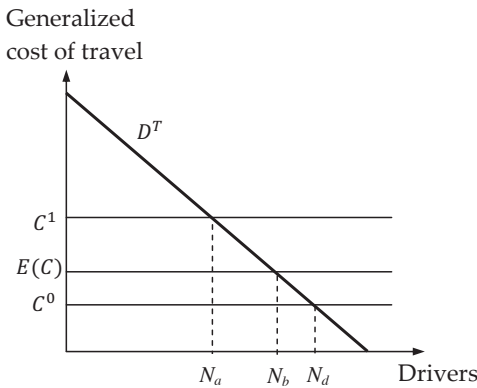
Potential drivers with a marginal benefit  $C^0 > D_j^T$  are not relevant for our discussion, as these drivers will never travel, and traffic information is of no use for them.

Figure 4.1a shows the underlying travel demand and supply setup, while Figure 4.1b illustrates the resulting pattern of  $wtp^I$  just discussed. The drivers

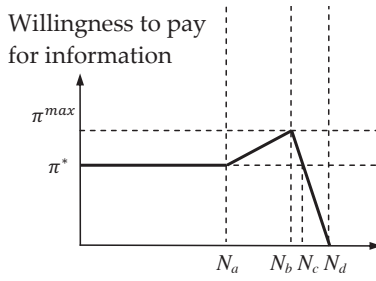
between  $N_a$  and  $N_b$  gain both a route choice and a participation benefit of information, with driver  $N_b$  having the highest  $wt p_j^I$ , as she obtains the maximum participation benefit. Drivers to the left-hand side of  $N_a$  enjoy a route choice benefit only. Drivers to the right-hand of  $N_b$  enjoy a participation benefit only.

Figure 4.1b shows  $wt p_j^I$  for each driver, maintaining the ordering of the inverse demand curve from Figure 1a. However, the inverse demand function for information that we are interested in should represent the relationship between the price of information  $\pi$  and the number of drivers willing to be informed  $N^I$ . Note that for the price  $\pi^{max}$ , which corresponds to the highest  $wt p_j^I$ , there is only one person, namely  $N_b$ , willing to acquire information. By changing the order of individuals to that order that reflects a declining  $wt p_j^I$ , we

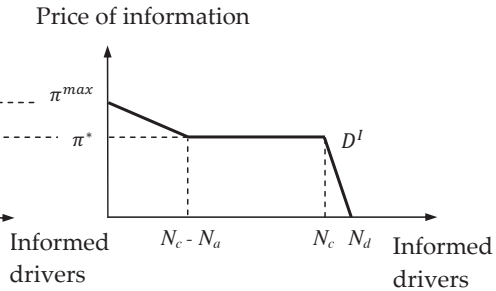
**Figure 4.1a.** Demand and stochastic costs of travel



**Figure 4.1b.** Willingness to pay for information



**Figure 4.1c.** Demand for information



transform Figure 4.1b into 4.1c, the latter thus giving the conventional inverse demand function for information. Using expressions (1), (2) and (3) we derive the following inverse demand function for information,  $D^I$ :

$$(4) \quad D^I = \begin{cases} (p - p^{n+1})(C^1 - C^0) - N^I a(1 - p^n)p^n & | \quad N^I \in (0; N_c - N_a) \\ (C^1 - C^0)(p - p^n) & | \quad N^I \in [N_c - N_a; N_c] \\ (1 - p^n)(d - C^0) - N^I a(1 - p^n) & | \quad N^I \in (N_c; N_d] \end{cases}$$

### 4.3 Pricing

#### 4.3.1 Pricing strategies under alternative ownership regimes

Under alternative ownership regimes of both a road operator and an information provider, we should expect different road and information pricing strategies. Table 4.1 lists the pricing strategies that we will consider and gives the subsections they will be studied in. “Marginal cost pricing” corresponds to the case where the operator sets the price that would maximize welfare if the other market were optimally priced. “Welfare-maximizing second-best pricing”, in contrast, refers to the case where the operator maximizes overall welfare given the distortion in the other market, and takes it into account in setting the second-best price on the own market.

**Table 4.1.** Subsections of this chapter that correspond to a particular pricing strategies combination

		Road operator’s pricing strategy		
		Profit-maximizing	Marginal cost	Welfare-maximizing second-best
Information provider’s pricing strategy	Profit-maximizing	4.3.3	4.3.2.1	4.3.4.1
	Marginal cost	4.3.2.2		
	Welfare-maximizing second-best	4.3.4.2		

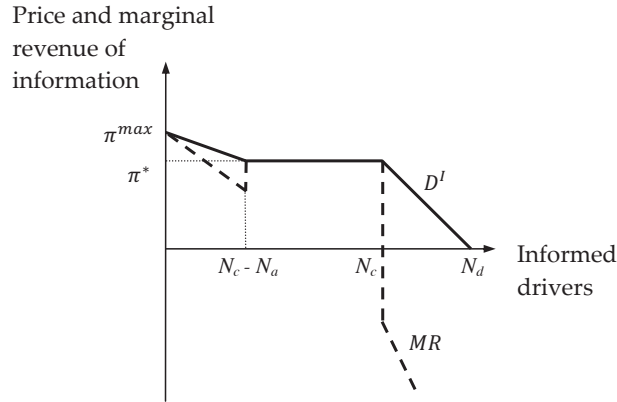
#### 4.3.2 Profit-maximizing pricing when the other price is at zero

##### 4.3.2.1 Information pricing when road is toll-free

A profit-maximizing information provider sets a price that equates marginal revenues ( $MR$ ) with marginal costs ( $MC$ ). Figure 4.2 shows the demand for and

marginal revenues of information provision. The kinked demand function derived in the previous section implies a discontinuous marginal revenue function, as the slope of marginal revenue line is twice as steep as the slope of the demand line.

**Figure 4.2.** Demand for (bold line) and marginal revenue (dash line) of information



For simplicity we set  $MC = 0$ . It is plausible that also in reality, given available technologies, after substantial fixed and/or sunk costs investments, the distribution of information to individual drivers is virtually costless. One might think of a subscription to a digital service. Moreover, below we show that the introduction of a positive  $MC$  does not affect the further analysis fundamentally, as long as it is sufficiently low.

When  $MC = 0$ , it is easy to prove<sup>31</sup> that the only intersection of  $MC$  and  $MR$  occurs when the number of informed drivers is  $N_c$ . Thus, the profit-maximizing price of information is  $\pi^*$ , which is equal to the route choice benefit; see Equation (1).<sup>32</sup>

<sup>31</sup> When the number of informed drivers increases from zero and approaches  $N_c - N_a$  the downward sloping section of  $MR$  function stays positive and thus  $MR$  intersects the horizontal axis only once. As long as  $MC < (C^1 - C^0)(p + p^{n+1} - 2p^n)$ , there is a unique local profit-maximizing price of information, which therefore is also globally profit-maximizing.

<sup>32</sup> It is also possible that the intersection of the  $MR$  and  $MC$  is to the right of  $N_c$ . However, the necessary condition for it is that a last kink of the  $MR$  is positive, which implies  $2(C^1 - C^0)(p - p^n) - (d - C^0)(1 - p^n) > 0$ . That implies  $2p - p^n > 1$  which might hold only when  $p > 0.5$  and

Interestingly, the introduction of information with a price  $\pi = \pi^*$  does not change the expected number of trips made in the network (this holds for  $\pi > \pi^*$  as well). It is easy to prove that the decrease in the number of expected trips by the drivers between  $N_a$  and  $N_b$  (see Figure 4.1b) is exactly offset by an increase in the number of expected trips by the drivers between  $N_b$  and  $N_c$ .<sup>33</sup> The first  $N_a$  drivers keep their overall number of trips constant. This exact insensitivity of the expected number of trips stems from the assumed linearity of travel demand, and will therefore disappear in more general formulation. The exact equality is not essential for what follows.

#### 4.3.2.2 Road pricing when information is free

The profit-maximizing firm levies a road toll ( $\tau$ ) to maximize its profit function  $\Pi(\tau)$ . When traffic information is not available to the drivers, the operator sets a usual monopolistic price, which depends on the reservation price  $d$  and expected cost  $E(C)$ , i.e.,  $\tau = 0.5(d - E(C))$ .

When information is free, the profit function of the road operator might fail to be quasi-concave. To identify the profit-maximizing road toll for a profit function that is not quasi-concave, one should check all stationary points and all corner solutions (e.g., Wolfstetter, 1999). As this complicates deriving an analytical solution for the profit-maximizing road toll, we will run numerical simulations. First, we give the intuition behind this point.

The complication stems from the fact that the road operator faces two pricing options, namely, either a relatively low road toll  $\tau_{low} \leq d - C^1$ , or a relatively high toll  $d - C^1 < \tau_{high} \leq d - C^0$ . The low toll is low enough to induce drivers with a high willingness to pay for travel (i.e.,  $D_j^T \geq C^1 + \tau$ ) to use the road irrespective of the travel cost. However, other drivers would abstain from travel when the cost of travel is high ( $C^1$ ). Thus, in a fraction  $p^n$  a road operator is not able to charge them. On the other hand, a high toll is prohibitively high for *all* the drivers when the cost is high, thus, in a fraction  $p^n$  the road operator is not able to charge *any* of the drivers.

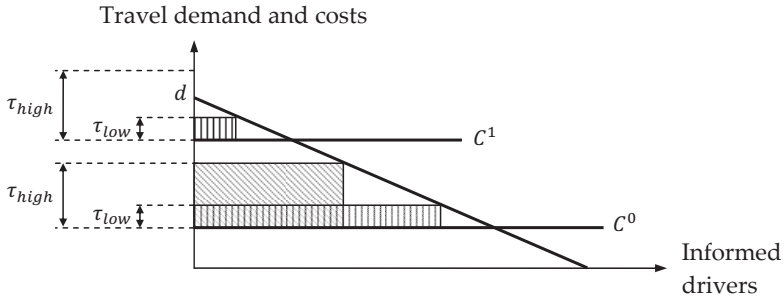
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$n \geq 3$ . For any practical purpose a probability of an incident on one route larger than 50 percent is hardly realistic, so we do not consider it in the analysis.

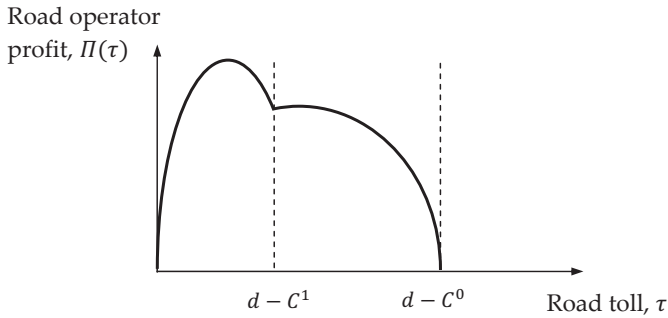
<sup>33</sup> Using equations (2) and (3), one can show that the road use declines by  $\frac{\pi^{max} - \pi^*}{a}$  for all drivers to the left from  $N_b$  (in Figure 4.1c) if the information price drops from  $\pi^{max}$  to  $\pi^*$ . For all drivers to the right from  $N_b$  the road use increases by exactly the same amount.

Figure 4.3 illustrates these two alternatives; the shaded areas represents road operator profits. Depending on the exact specifications of  $D^T$ ,  $C^1$ ,  $C^0$  and  $p$ , the firm will prefer either the profit under toll  $\tau_{low}$  or that under toll  $\tau_{high}$ . Figure 4.4 shows a hypothetical profit function that is not quasi-concave. In this example, a road toll  $\tau_{low} \leq d - C^1$  creates the highest profit. In the numerical exercise below, we of course always select the toll that is globally profit-maximizing.

**Figure 4.3.** A road operator profits under various tolls when information is free



**Figure 4.4.** A hypothetical road operator profit function  $\Pi(\tau)$  when information is free



### 4.3.3 Simultaneous information and road pricing: Bertrand-Nash behavior

#### 4.3.3.1 Reaction function of the information provider

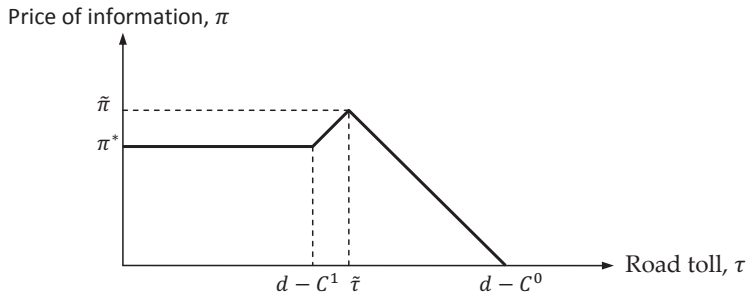
As we have showed before, a closed-form solution exists for the profit-maximizing information price  $\pi$ , and a road operator sets the profit-maximizing



road price  $\tau$  in the set of local maxima and corner solutions. In both cases, the price of the other service was assumed to be equal to zero. To effectively examine the effect of a positive road toll on information price (and vice versa), we determine the reaction function, also known as best-response function, of a private information provider and that of a private road operator, starting with the former.

The reaction function of an information provider shows the profit-maximizing price  $\pi$  as a function of a road price  $\tau$  (see Figure 4.5). We let some part of the inverse travel demand exceed the highest costs when the road toll is zero, i.e.,  $d \geq C^1$ . As established above, if the road toll is zero, the firm's optimal price of information is  $\pi^*$ .

**Figure 4.5.** Reaction function of the information provider

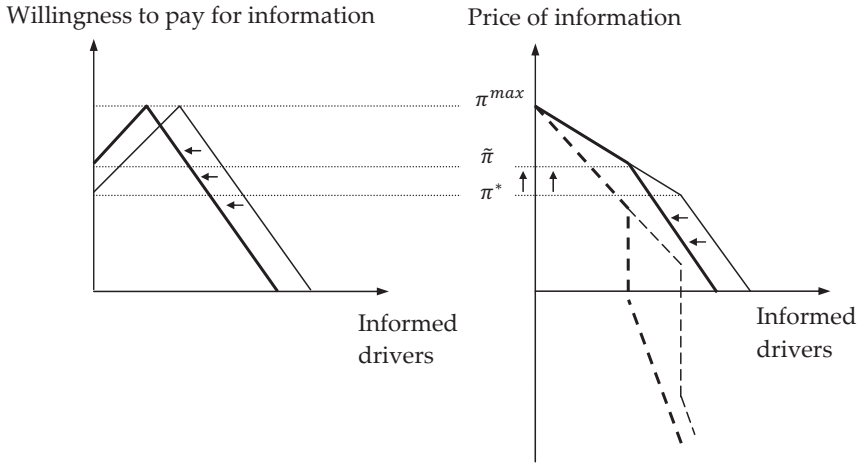


When the road toll increases by  $\tau \leq d - C^1$ , the number of drivers who travel irrespective of the travel cost decreases. Nevertheless, as long as these drivers are present in the market the information provider finds it most profitable to charge  $\pi^*$  for information. This can be confirmed by inspection of Figure 4.2 (or Figure 4.1c), in which the shape of the marginal revenue function remains unchanged with an increase of the road toll, apart from the horizontal section which shrinks (that section represents drivers who travel irrespective of the travel cost). But the reduction of the numbers of those drivers does not affect the profit-maximizing price.

When the road toll is  $\tau > d - C^1$ , all informed drivers abstain from travel when the cost of travel is  $C^1$ . An increase of the road toll reduces the amount of drivers, but those drivers who still travel have a relatively high participation benefit: information becomes more valuable as it helps to avoid the costs of an

**Figure 4.6a.** Willingness to pay for information when the road toll increases from  $\tau = d - C^1$  (regular line) to  $\tau = \tilde{\tau}$  (bold line)

**Figure 4.6b.** Demand for (solid lines) and MR of (dashed lines) information when the road toll increases from  $\tau = d - C^1$  (regular line) to  $\tau = \tilde{\tau}$  (bold line)



unbeneficial trip. That makes it appealing for the information firm to increase  $\pi$ . Hence, the reaction function in Figure 4.5 slopes upward beyond  $d - C^1$ .

Figure 4.6a illustrates how an increase of a road toll from  $\tau = d - C^1$  to  $\tau = \tilde{\tau}$  (to be defined below) shifts the willingness to pay for information function leftward. Analogously to Figure 4.1b, the order of the road users in Figure 6a corresponds to the order of drivers in the demand for travel. Figure 4.6b reorders those users, by  $wtp_j^i$ , to depict the inverse demand for and MR of information. The leftward shift in Figure 4.6a causes the intercept in Figure 4.6a, and hence the kink in  $wtp_j^i$  in Figure 4.6b, to shift upward. As long as the optimal price  $\pi$  is equal to the kink, the reaction function in Figure 4.5 is therefore positively sloped.

The higher the road toll, the smaller the number of drivers with both a route choice and a participation benefit of information. When the road toll is  $\tilde{\tau}$  the profit-maximizing information price is  $\tilde{\pi}$ . When the road toll is above  $\tilde{\tau}$ , the information price starts declining with the rise of a road toll, to capture consumer surplus of drivers who have only a participation benefit. Thus, the

reaction function kinks for the second time. We can derive the values of  $\tilde{\tau}$  and  $\tilde{\pi}$  as follows:

$$\tilde{\tau} = d - C^0 - \frac{2p(C^1 - C^0)}{1 + p^n}$$

$$\tilde{\pi} = \frac{(C^1 - C^0)(p - p^{n+1})}{1 + p^n} = \frac{\pi^{max}}{1 + p^n}$$

These values of  $\tilde{\tau}$  and  $\tilde{\pi}$  are derived by using information demand equation (4), and calculating  $MR$  functions when the downward sloping section of  $MR$  touches the horizontal line.

The kinked shape of the information provider's reaction function depicts an interesting relationship between  $\pi$  and  $\tau$ . For some range of a road toll,  $\tau \in [0, d - C^1]$ , the information price is strategically neutral. For a short range,  $\tau \in (d - C^1, \tilde{\tau}]$ , it is a strategic complement; and for the rest,  $\tau \in (\tilde{\tau}, d - C^0]$ , it is a strategic substitute.

#### 4.3.3.2 Reaction function of the road operator

It is difficult to identify the reaction function of a road operator, as it does not have a single closed-form solution. This is because a road operator considers two possible alternatives for a profit-maximizing road toll  $\tau$ : a relatively low road toll,  $\tau_{low} \leq d - C^1$ , and a higher toll,  $d - C^1 < \tau_{high} \leq d - C^0$ . In general, profits can be determined numerically. Nevertheless, we briefly outline the main characteristics of one relevant closed-form solution.

When the price of information is prohibitively high, i.e.,  $\pi > \pi^{max}$ , there are no drivers willing to acquire expensive information. The profit function of the road operator then has the following form:

$$(5) \quad \Pi_R = \tau \frac{d - E(C) - \tau}{a}$$

Note that this is identical, not surprisingly, to the profit function under the no information regime. The profit-maximizing price is then  $\tau = \tau_{low} = 0.5(d - E(C))$ .

It turns out that under parameter levels that we will consider in Section 4.4, the profit function, as given by equation (5), is not affected when the information price drops to the level  $\pi^{max} \geq \pi > \pi^*$ . Of course, information provision under price  $\pi^{max} \geq \pi > \pi^*$  will increase the consumer surplus of

informed drivers by  $wtp_j^I - \pi$ . However, the expected number of trips stays the same, as discussed in subsection 4.3.2.1, and road operator then charges the same toll.

At the price level  $\pi^*$ , those drivers with high travel demand  $D^T \geq C^1 + \tau$  will purchase the information to get a route choice benefit. Nevertheless, their acquaintance with information does not affect the road operator's profit, as these drivers do not change their travel decisions, since they always travel. As long as  $\pi \geq \pi^*$ , the road operator's profit function does not depend on the information price.

A further decrease of the information price, so that  $\pi < \pi^*$ , induces a road operator to increase a toll (see Figure 4.7). Drivers who previously did not travel will start buying information and will now travel in a fraction  $1 - p^n$  of the cases. The profit function of the road operator  $\Pi_R(\tau)$ , conditional on the toll  $\tau_{low} \leq d - C^1$  and  $\pi \leq \pi^*$ , is:

$$(6) \quad \Pi_R = \tau_{low} \left( \frac{d - C^0 - \tau_{low}}{a} - \frac{p^n(C^1 - C^0)}{a} - \frac{\pi}{a} \right)$$

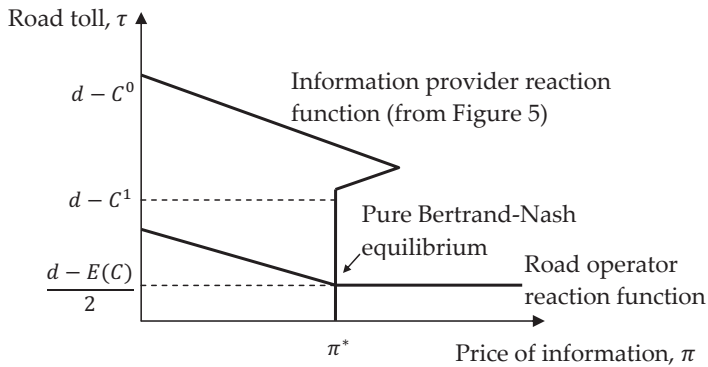
Note that the second term on the right hand side of the equation (6) is the amount of trips the drivers make when the price of information and the road toll are low.  $\frac{d - C^0 - \tau_{low}}{a}$  is the number of drivers willing to travel in low-cost state when the price of information is zero.  $\frac{p^n(C^1 - C^0)}{a}$  is the number of trips which drivers will abstain from in a fraction  $p^n$  of all cases.  $\frac{\pi}{a}$  is the number of drivers who will not be present in the market with a positive information price, compared to the free information case. The profit-maximizing road toll for the profit function (6) is  $\tau = \frac{d - C^0 - p^n(C^1 - C^0) - \pi}{2}$ .

Figure 4.7 shows the reaction functions of both a road operator and an information provider, where the intersection is a pure Nash equilibrium. This pure Nash equilibrium is a stable trembling hand perfect one, because a small deviation from equilibrium, e.g. by mistake, would induce the agents to return to the equilibrium prices.

Several outcomes of this Nash equilibrium follow immediately. First, as discussed before, the number of expected trips in the network under the no information regime and with profit-maximizing road pricing is the same as under the Nash equilibrium. Second, as can be seen from Figure 4.7, the road toll (and, given the first point, the profit of the road operator as well) is the

same as it is without information, i.e.,  $\pi^* \leq \pi < \infty$ . Third, the drivers with high willingness to pay for travel  $D^T \geq C^1$  do not gain additional consumer surplus from the introduction of information. These drivers gain route choice benefit of information which is exactly skimmed off by the information provider which sets price  $\pi^*$ .

**Figure 4.7.** Possible reaction functions of an information provider and a road operator



#### 4.3.4 Welfare-maximizing second-best pricing

##### 4.3.4.1 Second-best road pricing

We now turn to the case of welfare-maximizing pricing, where an operator might want to deviate from marginal cost pricing to address possible welfare distortions in the other market. A public road operator thus might want to subsidize road use, to compensate for an excessive private information price. And conversely, the public information provider might subsidize its service, to offset possible adverse impacts from monopolistic road pricing.

It should be explained that subsidizing as a policy instrument requires some reservations. Government subsidies are funded via taxation, which itself might be welfare-distortive. In practice, the marginal effect of the subsidies should be compared with the marginal cost of public funds. We do not cover this issue here, and thus implicitly assume an existence of a welfare-neutral lump-sum tax.

When the road toll is zero, the profit-maximizing price of information is equal to the route choice benefit  $\pi^*$ , which leads to inefficiency, as some drivers

who lack information abstain from travel, while they would travel when they are informed. To induce a higher road use, a public road operator might subsidize drivers by decreasing the cost of travel using the state-of-nature and driver independent subsidy  $\gamma > 0$ . One might think of a lump-sum transfer to each individual who makes a trip.

The road use subsidy does not change the profit-maximizing price of information, as this price is solely determined by the route choice benefit  $\pi^*$ , which stays unchanged, since the subsidy applies to both states of nature  $C^0$  and  $C^1$ . The subsidy then makes it beneficial for some drivers with demand  $E(C) > D_j^T \geq C^0$  to start acquiring information and make trips. These drivers will travel as long as the price they pay for information is lower than the sum of their initial consumer surplus and the subsidy, i.e.  $\pi^* < (D^T - C^0 + \gamma)(1 - p^n)$ . Note that the road use subsidy is conditional on the actual trip, whereas the price for information is paid all the time, also when drivers stay home (as in the case of a subscription). The newly generated trips are welfare-enhancing, providing that the benefit that drivers derive from those trips is higher than the cost of travel, i.e.  $D_j^T > C^0$ .

However, there is another group of drivers who alter their travel behavior due to government intervention. Some drivers, who previously traveled only in the fraction  $1 - p^n$  of cases (under cost  $C^0$  only), will begin traveling always (also under cost  $C^1$ ), as  $D_j^T > C^1 - \gamma$ . This causes a welfare loss, as the consumer benefit they receive is lower than the cost of travel, i.e.  $D_j^T < C^1$ . Note that under monopolistic information pricing, the number of drivers who travel under cost  $C^1$  is optimal and any additional trips generate losses. This occurs because the monopolistic information price  $\pi^*$  is such that it does not affect the participation decision of the drivers who travel all the time (drivers with travel demand  $D_j^T \geq C^1$ ). It is those drivers who should have been traveling under cost  $C^0$  who are negatively affected by monopolistic information pricing. Since a public road operator cannot separate these two groups, it needs to balance the welfare effects in order to achieve the highest additional welfare, while using a road subsidy as a second-best welfare-maximizing instrument. For other drivers, the subsidy is a pure money transfer with no behavioral and social welfare effects.

It is easy to prove that a subsidy  $\gamma$  attains the highest additional welfare when it is equal to the route choice benefit  $\pi^*$ . Although subsidizing is beneficial for society, it cannot achieve the first-best outcome. When  $\gamma = \pi^*$ ,

there are drivers who do not travel, as the price of information is too high, i.e.  $\pi^* > (D_j^T - C^0 + \gamma)(1 - p^n)$ . While the number of trips is the same as in the first-best scenario, the composition of trips is different, i.e. some of those who in the first-best case should be on the road, never travel (due to the high information price), while some of those who should travel only in  $1 - p^n$  percent of cases, travel all the time (due to the subsidy).

#### 4.3.4.2 Second-best information pricing

When the price of information is zero, the profit-maximizing road operator uses profit functions (such as (6)) to set the state-independent road toll. Although everyone is informed, not everyone who would travel in the first-best scenario is willing to do so under a monopolistic road toll. Hence, a public information provider might intervene to partly correct for this market distortion.

Consider a state-of-nature and driver independent information subsidy  $\delta > 0$  that is given to everyone who travels at least sometimes. Not surprisingly, the information subsidy as a welfare-enhancing instrument achieves the first-best outcome when  $\delta$  is equal to the road toll, which is also state-independent. Predictably, the road operator responds to the subsidy by an increase of the road toll. The information subsidy matches the increased road toll until the level when the number of drivers using the road is equal to the first-best case (we disregard a situation when road operator charges infinite price).

## 4.4 Numerical simulations

We examine nine different market forms of different ownership regimes listed in Table 4.2. We want to analyze the comparative static welfare implications of the various market arrangements, and to that end we use a parameterized numerical version of the model. We set the number of parallel identical routes to  $n = 2$ ; the cost of travel without a delay is normalized to  $C^0 = 1$  and the cost of travel with a delay is  $C^1 = 1.5$ . The probability of a delay on one route is  $p = 0.25$ , which corresponds to one delay per 4 trips. In the reference equilibrium we set  $N = 100$  to cast the discussion of the number of drivers into terms of percentages of the basic equilibrium under  $E(C)$ . Demand elasticity,  $e$ ,

under expected cost level,  $E(C)$ , is  $-0.4$ .<sup>34</sup> The reservation price of the inverse travel demand is 3.9375 and a slope of the inverse demand line is  $-0.028125$ .<sup>35</sup> A sensitivity analysis will investigate the robustness of our main findings.

**Table 4.2.** Alternative ownership regimes

	Road pricing	Information pricing	Remark
1	Marginal cost (free)	Not available	Base case: drivers make decision based on the expectations of the cost values
2	Marginal cost (free)	Marginal cost (free)	First-best pricing
3	Profit-maximizing	Not available	A lack of externalities makes road pricing a purely welfare-distortive market element
4	Profit-maximizing	Marginal cost (free)	If the information provider is unwilling or unable to insure excludability property of the information service, it becomes a public good
5	Marginal cost (free)	Profit-maximizing	
6	Profit-maximizing	Profit-maximizing	Bertrand-Nash pricing
7	Profit-maximizing collusion		A single monopolist owns both road network and provides traffic information about it
8	Profit-maximizing	Second-best subsidy	Public information provider tries to correct the distortion on the road market
9	Second-best subsidy	Profit-maximizing	Public road operator tries to correct the distortion on the information market

<sup>34</sup> A long-term commuting car time elasticity in the EU is equal to  $-0.4$  (de Jong and Gunn, 2001).

<sup>35</sup> In equilibrium,  $E(C) = d - aN$ , thus  $d = E(C) + aN = E(C) + \frac{E(C)}{N \cdot |e|} N = E(C) \left(1 - \frac{1}{|e|}\right)$ .



The results of the baseline simulations are in Table 3. For each of the nine market forms we indicate both the road toll and the information price. The number of potential drivers shows the amount of drivers who would travel on the road in the low-cost state ( $C^0$ ), under the given road toll and information price. The number of expected trips either equals the number of potential drivers, or it is lower, because informed drivers with travel demand  $C^1 > D_j^T \geq C^0$  abstain from the trip in  $p^n$  percent of the time when the travel cost on all routes is  $C^1$ .

We ignore fixed costs in our model. The profit from the information provision is therefore the product of the information price and the number of potential drivers. Note that not all drivers have to be informed – a driver might use a road network without buying information. Nevertheless, our simulation results show that every potential driver will acquire information, if information technologies are available, in all ownership regimes that we consider. As a general rule, to find profit from the information provision, we have to multiply the information price by the number of drivers willing to be informed. Profit from the road operation is given by the product of the road toll and the expected number of trips.

We show consumer as well as producer surplus, the latter being the sum of information and road profits. We compute government spending on the subsidies in the last two market arrangements. Social welfare is the sum of consumer and producer surpluses minus government spending. The last row of Table 3 presents the ranking of the social welfare outcomes.

The results are more informative if one reports the relative efficiency of the market setups,  $\omega$ , instead of the nominal values of social welfare. Following Arnott, et al. (1991), we define the relative efficiency  $\omega$  of the market setup  $i$  as:

$$(7) \quad \omega_i = \frac{welfare_i - welfare_{ref}}{welfare_{fb} - welfare_{ref}}$$

where  $welfare_i$  is the social welfare that the market setup  $i$  generates,  $welfare_{ref}$  is the social welfare that the reference market form produces (in our case it is “free road, no ICT” market) and  $welfare_{fb}$  is the social welfare under first-best conditions (i.e. marginal cost pricing “free road, free ICT”). Hence,  $\omega$  equals zero in the reference equilibrium and equals one for the first-best market arrangement. A positive  $\omega$  indicates that the market setup performs better than

the reference one. A negative  $\omega$  indicates a reduction in social welfare as compared to the reference case.

Predictably, a market with marginal cost pricing (“free road, free ICT”) generates the highest social welfare. The pool of potential drivers is the largest of all cases we consider. The number of expected trips is lower than the number of potential drivers, because in 6.25 percent of time drivers with travel demand  $C^1 > D_j^T \geq C^0$  do not travel while being informed.

A market with second-best information subsidies and private roads (“private road, ICT subsidy”) mimics the first-best welfare outcome. The information subsidy exactly compensates for the road toll, and hence fully covers the profit of the private road operator. Prices allow the same number of drivers and expected trips as in the first-best marginal cost pricing arrangement.

A market with second-best road use subsidies and private information (“road subsidy, private ICT”) is only slightly less efficient than the first-best. The road use subsidy,  $\gamma$ , equals the information price, and almost all information profit is financed by subsidies. Note that the producer profit is a bit larger than government spending, as drivers always buy information, but do not always travel and thus do not always receive subsidy. Hence, drivers have to pay the difference. The monopolistic information price prevents some drivers with a willingness to pay for travel higher than  $C^0$  to make trips. Therefore, the number of potential drivers is lower than the first-best.

An untolled road network with private information provision (“free road, private ICT”) yields a social welfare close to the first-best market form. It is interesting to note that monopolistic information pricing has a very small distortive impact on social welfare. In fact, the social welfare difference between the first-best “free road, free ICT” market and “free road, private ICT” market is negligible in our parameterization. While private information decreases the consumer surplus, the decline is to a large extent offset by the producer surplus rise. The profit-maximizing information price is such that the resulting social welfare deadweight loss is rather small (in Figure 4.1c, the deadweight loss is represented by the area below the demand curve to the right from  $N_c$ ).

The non-existence of congestion in our model makes a positive road toll welfare-distorting. The private road with free information is ranked the 6<sup>th</sup> out of the 9 market forms we consider. The social welfare is substantially lower in comparison to the above mentioned markets.

**Table 4.3.** Characteristics of various market arrangements based on the baseline numerical estimations

Market forms	Base case: free road without ICT	First-best marginal cost pricing	Private road without ICT	Private road with free ICT	Free road with private ICT	Bertrand- Nash	Private collusion	Private road with public ICT subsidy	Private ICT with public road use subsidy
Information price	NA	FREE	NA	FREE	0.09	0.09	0.09	-2.94	0.09
Road toll	FREE	FREE	1.41	1.45	FREE	1.41	1.36	2.94	-0.09
Number of potential drivers	100.00	104.44	50.00	52.78	100.89	50.89	52.56	104.44	104.22
Number of expected trips	100.00	103.33	50.00	51.67	100.00	50.00	51.67	103.33	103.33
Information profit	NA	0.00	NA	0.00	9.46	4.771	4.93	0.00	9.78
Road profit	0.00	0.00	70.31	75.078	0.00	70.312	70.23	303.54	0.00
Producer surplus	0.00	0.00	70.31	75.078	9.46	75.083	75.16	303.54	9.78
Consumer surplus	140.62	150.42	35.16	37.80	140.79	35.32	37.71	150.42	150.32
Government spending	0.00	0.00	0.00	0.00	0.00	0.00	0.00	303.54	9.69
Social welfare	140.62	150.42	105.47	112.88	150.25	110.41	112.87	150.42	150.41
Relative efficiency, $\omega$	0	1	-3.59	-2.833	0.98	-3.09	-2.835	1	0.999
Welfare rank	5	1	9	6	4	8	7	1	3

Somewhat surprisingly, the 7<sup>th</sup> market arrangement in our ranking is the private collusion scenario, when one profit-maximizing firm controls both an operation of the road network and a provision of the traffic information about it. The Bertrand-Nash case of independent monopolists performs worse than collusion in terms of social welfare. The mechanism behind this effect resembles double marginalization, when a single monopolist charges a lower overall mark-up compared to the joint effect of two separate, complementary firms mark-ups. But our case is slightly different.

To remind, double-marginalization refers to the situation where the consumer price exceeds the conventional monopolistic price, because two monopolists set their prices independently with the goal to maximize their own profits. The monopolists could be vertically separated (i.e., one supplies an input to the other), or could supply complementary goods. The sum of the two prices is then higher than what a single monopolist, controlling both firms, would charge, as the independent firms do not take into account the negative effects of their prices on the profit of the complementary firm. The case of the road network and traffic information resembles the complementary goods case, although it is slightly different because there is no strict complementarity: a driver can use the road without being informed, while it makes no sense to be informed without making any trips. Hence, there is no strict complementarity, and moreover, there is an asymmetry in the interdependence. Still, with private road and private ICT market we find a result known from the double marginalization literature, namely, that independent road operation and information provision pricing leads to an overall mark-up that exceeds the monopoly mark-up from a single combined private supplier. This, in turn, leads to a social welfare level below that of a single monopoly.

Referring back to the simulation results, the sum of the equilibrium information price and a road toll under a collusion scenario is equal to the equilibrium private road toll with free information ("private road, free ICT").<sup>36</sup> Although the monetary costs are equal in those two cases, the cost composition is different. That leads to a difference in the number of potential drivers and, consequently, in the welfare levels. A monopolist attracts more potential drivers by setting a lower road toll. It trades off the profit from the road toll with the profit from the information provision. While some profits from the road

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<sup>36</sup> The equality holds true under specific parameter values, due to travel demand linearity.

operation will be lost, revenues from information provision more than compensate for that loss.

As expected, the least preferable market form from the social perspective is the private road without information. There are relatively few potential drivers, and the consumer surplus is lower than in any other scheme considered.

#### 4.5 Sensitivity analysis

In order to get a better understanding of the key determinants of the relative performance of the different market structures, we perform some sensitivity analysis. We will focus on the impacts of changes in the incident probability  $p$ , and the travel demand elasticity  $e$ . We start with the former, which shows the influence of the variability of travel times on social welfare.

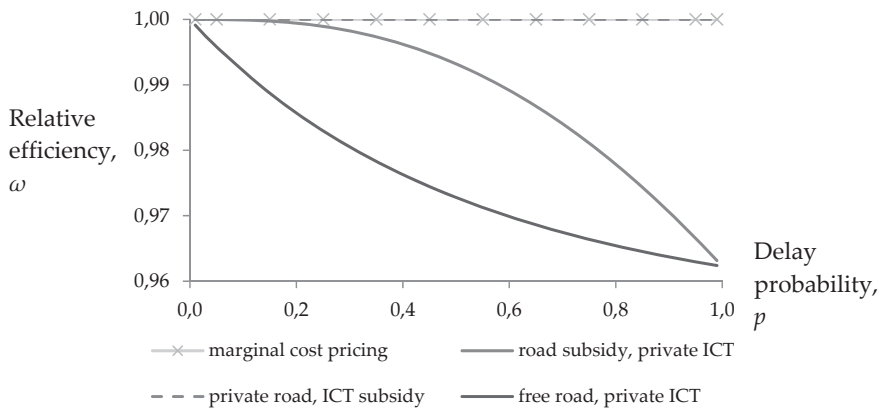
We want to test the effect of one parameter change on the simulation results, keeping everything else the same. The initial reference market is the “free road, no ICT” case. To keep the initial equilibrium the same (the number of potential drivers, the elasticity level), we need to keep the expected cost constant while adjusting  $p$ . When we change probability, we therefore move the stochastic cost levels simultaneously such that the expected cost  $E(C)$  remains constant. In doing so, we also keep the difference  $C^1 - C^0$  constant.

Figures 4.8a and 4.8b show the result. We split them up because the ideal scale is quite different for regimes where a private road price applies (Figure 4.8b), versus where it either does not or where its effect is entirely neutralized through a subsidy on ICT. Figure 4.8a then shows how the relative efficiency of the latter scheme is equal to one; i.e., to marginal cost pricing: the subsidy induces every driver to acquire information, and compensates for each of the them for the excessive private road price.

For the other regimes the relative efficiency of private ICT with a road subsidy is naturally higher than for a free road, as the former is used to (imperfectly) compensate for overpricing by the private ICT supplier. It may seem surprising that when  $p = 1$  is approached, the relative efficiency of both schemes is still below 1, unlike what is found close to  $p = 0$ . The easiest way to see the working of the asymmetry is to examine Figure 4.1a and Figure 4.1b. When  $p$  approaches 0, the expected cost  $E(C)$  is close to  $C^0$ , that makes a group of drivers who would only use the road in the low-cost case relatively small,

and number of drivers who do not buy information is even smaller in equilibrium. However, when  $p$  approaches 1, the expected cost differs from  $C^0$  to a larger extent, which makes the number of drivers who travel only when informed much bigger. Moreover, among these drivers there are many who do not travel at all as they are priced off the market due to the monopolistic information pricing.

**Figure 4.8a.** Relative efficiency of the market setups as a function of the delay probability  $p$ , under constant expected cost  $E(C)$



**Figure 4.8b.** Relative efficiency of the market setups as a function of the delay probability  $p$ , under constant expected cost  $E(C)$

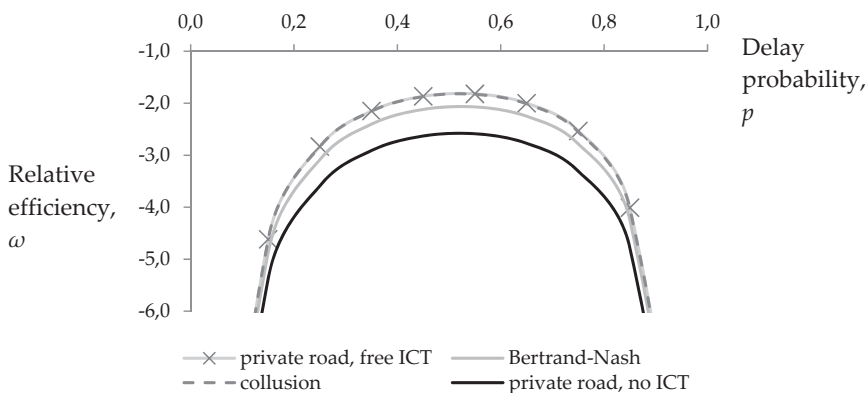
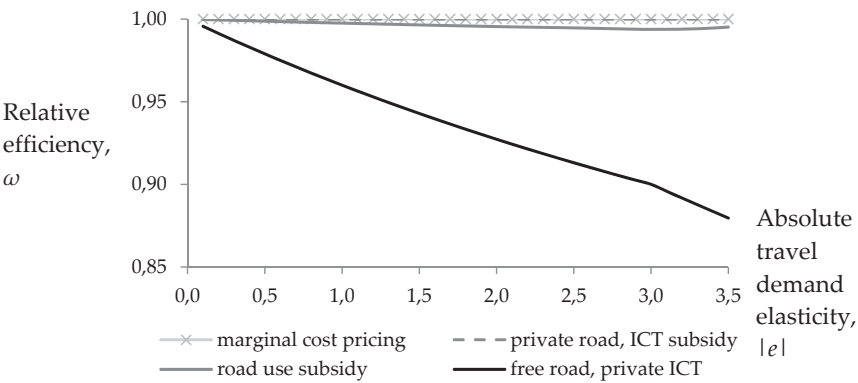
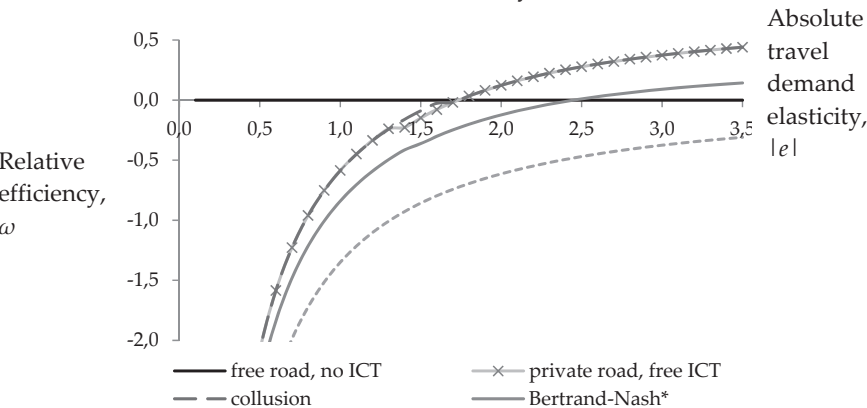


Figure 4.8b shows that the relative performance of schemes with private road supply is quite bad. The order of the schemes is the same as in Table 3, so that seems quite robust with respect to the incident probability. The similar shapes are due to the pattern in the identical denominator in these  $\omega$ 's: the gain from optimally priced ICT compared to the reference equilibrium with no information is largest, and hence the absolute value of  $\omega$  is smallest, when variability is greatest; that is close to a probability of 0.5.

**Figure 4.9a.** Relative efficiency of the market setups as a function of travel demand elasticity  $e$



**Figure 4.9b.** Relative efficiency of the market setups as a function of travel demand elasticity  $e$



Figures 4.9a and 4.9b show the patterns of  $\omega$  as a function of the elasticity of demand (absolute value). To keep reference equilibrium the same, the intercept and slope of the inverse demand were change simultaneously, keeping  $E(C)$  the same in equilibrium. Figure 4.9b shows that uncompensated private operation of the road produces higher efficiency losses as demand becomes less elastic. This is entirely in line with expectations. Otherwise, the ranking again appears robust.

Figure 4.9a shows how  $\omega$  for private ICT with a free road falls as demand becomes more elastic. The intuition is that a greater elasticity means that more drivers would potentially benefit from participation decisions besides route choice benefits. This increases the ICT provider's market power, and hence the degree of overpricing. Furthermore, the ICT subsidy can again compensate for private road overpricing, and also the road use subsidy policy can quite accurately compensate for private ICT overpricing. The results, in summary, remain robust.

#### 4.6 Summary and conclusions

We studied the welfare effects of information provision in the context of a market where potential drivers are facing a choice of whether to make a trip and, if so, which route to take. Due to the stochastic travel time and hence cost, they are willing to pay for information about the actual travel time. From a travel demand-supply setup, we derived an endogenous demand for information. We showed the profit and welfare maximizing pricing strategies of both a road operator and an information provider, while accounting for the interdependency between those strategies. Using numerical simulations we examined nine market forms with different ownership regimes, and compared the social welfare they generate. Sensitivity analysis proved the robustness of the main findings.

The analysis sheds light on some welfare implications of information provision. Interestingly, it does not matter much whether the information is provided by a public or a private company. Because of the kinked shape of the endogenous demand for information, the dead-weight loss created due to the monopolistic mark-up is relatively small. The dead-weight loss in the transport market is even smaller if the government can compensate for the inefficient information pricing with a public road use subsidy. When the road operator is a



profit-seeking firm, the Bertrand-Nash price equilibrium yields a lower social welfare in the market with a private information provider, than when information is free. But the difference in social welfare is not large. The main pricing strategy of the private information firm is to skim off the consumer surplus of those drivers who will travel irrespective of the travel costs, which requires an equalization of the information price to the route choice benefit. Essentially, the price mark-up hardly affects overall social welfare, but only redistributes some part of welfare from consumers to information monopolist. There are relatively few drivers who are left outside the market due to monopolistic information pricing.

Second, it seems that private collusion is a better market arrangement than a market with independent profit-maximizing road and information operators. Traffic information is not a pure complementary product to road use. Nevertheless, comparable to the conventional double-marginalization case, the mark-up of a single monopolist is lower than the sum of two independent mark-ups. This leads to a higher social welfare under a monopolistic market form than under two separate firms. There appears, therefore, little reason to prevent private road operators from offering paid information on traffic conditions on their roads. It is not true that this raises their market power and would therefore induce higher prices than separate firms would charge.

Of course, the numerical results pertain to a specific parameterization of a simple linear model. It is therefore useful to ask to what extent these results may be generalizable. First, the logic of route choice benefits constituting an upper limit of the willingness to pay for information for most drivers seems quite general. Second, the linearization of the main function may be unrealistic, but may still give a reasonable approximation when changes in cost levels are not too large. Third, feedback effects through congestion were suppressed for the sake of simplicity, and defended by the observation that both private and public road operators would internalize this, making it less of an issue when comparing such market forms. We do consider it, however, a useful extension for future work to relax this assumption.

There are, of course, several other possible extensions one might consider to incorporate into the analysis. It would be interesting to relax the assumption of homogeneity of drivers with respect to value of time. One can also expand the model by an introduction of sequential routes, or a toll-free public route as an alternative to the private routes. Furthermore, a probability of delay and a

cost of travel might be set as a function of a road operator's investment. More research is therefore still needed to obtain a more comprehensive view of the effects of information provision on social welfare.



## 5 Teleworking technology and travel

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### 5.1 Introduction<sup>37</sup>

John Maynard Keynes in 1930 infamously envisioned the future in which, thanks to technological progress, a fifteen-hour working week would be the norm. While for many individuals who currently endure a forty-hour working week this prediction might stand as wishful thinking, it is widely accepted that technological progress positively affects productivity and output growth (Jorgenson et al., 2008; Commander et al., 2011), although not necessarily hours worked (e.g., Pissarides, 2000). Ongoing advancement in information technology which is probably the most spectacular technological development over the past two decades strongly affects the ways people perform their job duty. This chapter takes a closer look at one such aspect by examining the causal long-run effect of information technology on commuting.

It is nowadays quite common that a job duty is subdivided into separate job tasks which might be performed at locations other than the conventional workplace. Residential location is one of the places where employees might carry out job tasks by engaging in teleworking, an out-of-office work arrangement, for some days of the week or hours of the day. Until the nineties, teleworking was mainly associated with (low-paid) manual jobs (see IDS, 1996). However, it has become increasingly relevant for other types of jobs as well, largely due to the continuing technological progress with regard to telework-enabling technology, such as e-mail, smartphones and Internet. For example, EU average incident rates of teleworking among employees were around 4% and 7% in, respectively, 2000 and 2005, – but with large variations between countries and industries (Eurofound, 2005, 2010). Potential benefits from increased teleworking adoption, which include, among others, reduced congestion, better work-life balance (James, 2014), improved job matching and higher productivity (while the latter might be debatable due to shirking, Bloom

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<sup>37</sup> This chapter is based on a joint work with Jos van Ommeren and Thomas de Graaff.

et al. (forthcoming) provide quasi-experimental evidence of a positive effect of teleworking on the routine tasks performance), have led many governments to develop friendly policy measures towards adoption of teleworking technology. For instance, the US Telework Enhancement Act of 2010 endorses teleworking among public employees, while the European Framework Agreement on Telework in 2002 promotes telework-friendly policies in the EU.<sup>38</sup>

Despite strong policy support for teleworking technology adoption, not least on the ground of its mitigating effects on the negative externalities of transport, such as congestion and pollution (de Borger and Wuyts, 2011), the possible countervailing causal effect of improved information technology on commuting distance travelled has never been convincingly estimated. Previous research has been largely descriptive, mostly due to lack of data; see discussions on causality identification in Mokhtarian et al. (2004) and Moos and Skaburskis (2008). It is neither straightforward to anticipate the sign of the technology effect based on economic theory. If an employee works from home for some days during the week, then the number of trips to work is reduced.<sup>39</sup> However, teleworking might also result in a relocation of residential and employment sites that changes the commuting distance per trip.

One might argue that the possibility to telework may induce individuals to choose their residential locations further away from the workplaces or, alternatively, choose workplaces which are further from home, so the commuting distance (per trip) increases. Lund and Mokhtarian (1994), Safirova (2002), Rhee (2008) and Glaeser (2008, p. 41) provide urban economic models on the relocation of households due to teleworking technology, which show that commuting distance might be longer for a teleworker than for other commuters. Technological progress not only has allowed workers to perform tasks at home, but it also has allowed many workers to perform tasks at other work locations than their own work place, which provides an even stronger incentive to workers to lengthen their commute. Thus, such long-run behavioral response of employees to teleworking technology might, in principle, be detrimental for social welfare, as negative transport externalities, for example, congestion and pollution, might aggravate.

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<sup>38</sup> Several governments have official Internet pages that endorse teleworking, for example, <http://www.telework.gov.au> in Australia and <http://www.telework.gov> in the USA.

<sup>39</sup> In a similar fashion, an employee who teleworks part-time during the day, to avoid peak period congestion, experiences a lower generalized commuting cost as well.

In these models, however, it is ignored that technology might also affect non-teleworking employees within firms where relatively many people telework. For example, people who expect to telework in the future are more likely to choose a residential location further away from the job if this job allows for teleworking. Alternatively, due to new technology, firms might find it profitable to locate away from central urban places with high land rents and instead, to save on land costs, locate in cheaper places that might be closer to residential locations. As the argument goes, progress in information technology in general and teleworking in particular might weaken agglomeration economies because face-to-face interactions of workers employed by different firms are less frequent and thus might be less valuable (see, for example, literature surveys by Anas et al. (1998) and Audirac (2005)). This, in part, motivates us to focus on a long-run effect of technology adoption on commuting distances for both teleworkers and non-teleworkers, which is an empirical question that this chapter will investigate.

To answer this question, one has to estimate the teleworking technology effect on commuting distances of both teleworkers and non-teleworkers, within the same professions, while accounting for reverse causality and omitted variable bias.<sup>40</sup> The issue of reverse causality is fundamental in the estimation of the effect of technology adoption on commuting distance, as employees who commute long distances might have stronger incentives to telework. Thus, a naïve OLS approach of explaining employees' commuting distance by teleworking would then produce biased estimates (likely to be overestimates). An experimental setup, in which the opportunity to use telework-enabling technology would be provided to only one of two otherwise identical groups of employees is one of the ways to avoid this bias and estimate the average causal effect (see, e.g., Angrist and Pischke, 2008). The major disadvantage of this approach, provided that it is feasible, is the short-run nature of a typical experiment in comparison to the effect of teleworking on commuting distances which manifests itself over the long term through changes in workplaces and home locations. An instrumental variable approach is another alternative. However, an instrument for the use of teleworking technology that does not

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<sup>40</sup> For example, workers with larger residences are more likely to live further away from the workplace and are more likely to prefer to work from home.

correlate with commuting distance is hard to find, as commuting distance and teleworking are both related to behavior in labor and housing markets.<sup>41</sup>

In this study we introduce a methodology that uses information from two years – one year when telework-enabling technology was not present and a more recent year when teleworking is technologically possible and adopted in some professions. We employ cross-sectional Dutch Labor Force Surveys for the years 1996 and 2010. The telework-enabling technology of 2010, such as high-speed Internet and powerful computers, was generally not available in 1996.<sup>42</sup> In contrast, Internet and powerful computers were pervasive in 2010. We also note that technological progress affects production functions of various professions in a different way, making telework a more feasible arrangement in some professions than in others. Such variations in teleworking adoption over time and professions will allow us to infer the causal effect of interest through difference-in-differences after applying propensity score matching.

In a nutshell, we compare the commuting distances of employees in 2010 who work in *teleworking professions* – we define these professions based on a minimum share of teleworkers in 2010, a year when the use of teleworking technology is common – with commuting distances of comparable employees in the same professions in 1996 who, by assumption, did not have access to teleworking technology. To find comparable employees in teleworking professions, we match employees from 2010 and 1996. The difference in commuting distance between these matched employees defines the change in the average commuting distance due to teleworking technology after correcting for a general time trend. We define this trend by the difference in commuting distance of matched employees from 2010 and 1996 in *non-teleworking professions* – which are defined to have no teleworkers at all. We interpret the resulting difference-in-differences estimate as the average causal effect of teleworking technology on commuting.<sup>43,44</sup>

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<sup>41</sup> Zhu (2012; 2013) analyses the effect of teleworking adoption on teleworkers and employs “Internet use at home” as an instrument for teleworking. However, when unobserved professional abilities of employees are correlated with the use of teleworking technology, such as Internet, then the instrument is not valid. So, this strategy implicitly assumes the absence of such connection. Our identification strategy avoids such a restrictive assumption.

<sup>42</sup> Note, that we will *not* assume that the teleworking incidents rate was zero in 1996. Our estimation approach allows for the possibility that employees were working from home in 1996.

<sup>43</sup> The question why some employees adopt available teleworking technology to a greater extent than others is outside the scope of this study. Multiple factors affect technology adoption, including managerial practices which preclude employees from teleworking (for example,

We find no evidence that the adoption of teleworking technology causes commuting distances to increase in professions where a substantial share, more than 5%, of its employees, is teleworking, compared to non-teleworking professions. In both profession types, the distance in the average commuting distance between 1996 and 2010 increased by about 2 km. We also find that non-teleworkers in teleworking professions commute shorter distances than in non-teleworking professions. The latter finding is harder to explain and this puzzling result warrants a further analysis. Empirically it turns out that on average (across professions) the commuting distance does not change due to technology adoption, as an increase in commuting distance of teleworkers is countervailed by a decrease in the commuting distance of non-teleworkers. Overall, this result suggests that teleworking technology adoption might be suitable to fight congestion, as we find that the technology is neutral with regard to commuting distance, and therefore average commuting kilometers travelled does not increase due to teleworking technology adoption.

The chapter is organized as follows. Section 5.2 presents the identification strategy and inference. Section 5.3 gives an overview of the data, provides definitions of teleworking and non-teleworking professions and presents results of the matching procedures and difference-in-differences estimate together with the robustness checks. The last section concludes with the discussion of the results.

## 5.2 Methodology

### 5.2.1 Identification strategy

This chapter aims to estimate the long-run change in commuting distances caused by the availability of teleworking technology. An ideal experimental study to uncover the causal effect of interest would be to randomly supply this technology to some professions, so there is a group of treated professions with and a group of untreated professions without technology (Angrist and Pischke, 2008). Then, after a certain time period, a comparison of both groups' average

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Yahoo! forbade teleworking in 2013), or certain characteristics of the labor market which render teleworking less beneficial, for example, when commuting distances are short (Mokhtarian, 1998).

<sup>44</sup> As we explain later, our method differs from “difference-in-differences propensity score matching” methodology (e.g., Hijzen et al., 2013), which relies on panel data to observe same individuals or firms over time.



commuting distances would identify the causal effect. This hypothetical experiment must take a considerable period of time as changes in home and work locations induced by workers occur infrequently (e.g., Zax, 1991). Also changes in distance due to workplace relocations induced by employers who have an incentive to change the workplace location of treated and untreated professions will often take quite a considerable time (Mulalic et al., 2014). Obviously, this ideal experiment is infeasible. We propose an alternative identification strategy that is based on observational data, which, arguably, comes close to this ideal setup. In essence, we intend to estimate the following expression:

$$(1) \quad E[Y_j | d_j = 1] - E[Y_j | d_j = 0], \text{ for } j = 1$$

where  $Y_j$  refers to the commuting distance of an individual who works in profession type  $j$ . We distinguish between non-teleworking ( $j = 0$ ) and teleworking professions ( $j = 1$ ). The treatment dummy  $d_j$  equals 1 if the technology is used by a substantial share of employees in profession  $j$ ;  $E$  denotes the expectation operator. In our empirical application, we will use different thresholds that define such a “substantial share” and will focus on professions with relatively small shares of teleworkers in the sensitivity analysis.<sup>45</sup> The treatment dummy  $d_j$  equals 0 if none of the employees is teleworking. Our definition of  $d_j$  captures the impact of adoption of teleworking technology on commuting distance of *all* employees in a profession (and not only of the share who are observed to telework during a certain period). Including employees in teleworking professions who do not telework is essential, because of a measurement error or because firms might change their location due to new technology. In addition, the possibility of using the technology in the future may affect workers’ current commuting distance. For example, workers who prefer to work from home in the near future (e.g., as they expect children) are more likely to move their residence further away from the job (e.g., to the suburbs) when this job allows for teleworking (van

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<sup>45</sup> The main advantage of using a binary measure of teleworkers share is that it drastically reduces the effect of measurement error in our teleworking variable. It seems reasonable to expect the effect of teleworking on commuting to be stronger the larger is the share of adopters within the profession. We confirm this assertion by repeating the entire analysis using data on professions with relatively low adoption rates, as we find no effect of technology on commuting.

Ommeren et al., 1999). This possibility is consistent with several studies that point out that many employees may telework for a short period (Bailey and Kurland, 2002).

To estimate  $E[Y_1|d_1 = 1] - E[Y_1|d_1 = 0]$ , i.e., the average treatment effect on the treated, where the treatment is the adoption of the technology in the profession, we start from the observation that telework-enabling technology, such as e-mail and Internet, were not widely available to, and hardly used by, workers in any professions in a certain year 0, but widely available to many workers in year 1.<sup>46</sup> We also observe that in year 1 the probability of teleworking differs strongly among professions due to differences in the production functions which require certain professions to be present at the workplace, whereas other professions are more footloose (conditional on available technology). One might think, for example, of a hospital doctor who has to be present at the workplace and a graphic designer who might work from home on certain days of the week in year 1, but not in year 0. It is then plausible that the designer chooses a longer commuting distance in year 1. At the same time, in year 1 organizations may relocate the workplace of designers closer to their residence locations (e.g., from the central business district to the suburbs), as the new technology may make it beneficial to locate further away from other business organizations. We will exploit variations in adoption of teleworking across professions and time to infer the causal effect of teleworking technology on commuting distance.

Formally, we observe the average commuting distance in year 1 of a group of employees who work in teleworking professions (and who are comparable in observed characteristics to those in teleworking professions in year 0). We also observe the average commuting distance in year 1 of employees who work in non-teleworking professions (and who are comparable in observed characteristics to those in non-teleworking professions in year 0). We denote both average commuting distances for these groups as  $E[Y_j|d_j = j; t = 1]$ , where  $t$  denotes the year of observation. The long-run causal effect of technology is defined by:

$$(2) \quad E[Y_1|d_1 = 1; t = 1] - E[Y_1|d_1 = 0; t = 0] \\ - (E[Y_0|d_0 = 0; t = 1] - E[Y_0|d_0 = 0; t = 0])$$

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<sup>46</sup> In our application we will use the years 1996 and 2010.

where the first row is the change over time in average commuting distances of employees in *teleworking professions*. This difference may be attributed to a general time trend in commuting distances (e.g., due to changes in the transport infrastructure supply, the spatial structure of the build environment or income) and the effect of the adoption of the technology. The second row captures the change over time in the average commuting distances for employees in *non-teleworking professions*. The latter difference reflects solely a general time trend (as neither in year 1 nor in year 0 the technology is adopted).

We subtract and add the term  $E[Y_1|d_1 = 0; t = 1]$ , which refers to the average commuting distance of employees in teleworking professions in year 1 if they would not have adopted the technology. So, (2) can be rewritten as:

$$(3) \quad \begin{aligned} & E[Y_1|d_1 = 1; t = 1] - E[Y_1|d_1 = 0; t = 1] \\ & + E[Y_1|d_1 = 0; t = 1] - E[Y_1|d_1 = 0; t = 0] \\ & - (E[Y_0|d_0 = 0; t = 1] - E[Y_0|d_0 = 0; t = 0]) \end{aligned}$$

The first row of (3) is the average treatment effect on the treated in year 1. The second row is a time trend which shows how commuting distance would have changed for employees who work in teleworking professions if the technology was not adopted in these professions in both years. The third row is the same as the last row of (2). To identify the causal effect, we assume that the time trends in average commuting distance for workers in non-teleworking professions and for workers in teleworking professions are identical if teleworking technology would not have been available to them, i.e., the second and the third rows in (3) are assumed to be equal. In other words, on average across professions time trends are the same. This same-trend assumption seems reasonable given the common exposure to changes in the (national) transportation infrastructure, changes in housing markets and the general development of the economy. We cannot 100% exclude the possibility that both trends differ for reasons not related to the new technology. However, there are no good reasons to believe that our key identification assumption does not approximately hold.<sup>47</sup>

Given this assumption, we can write (3) as:

$$(4) \quad E[Y_1|d_1 = 1; t = 1] - E[Y_1|d_1 = 0; t = 1]$$

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<sup>47</sup> Teleworking and non-teleworking professions comprise of many different professions, so we allow for the possibility that *some* professions have a different trend.

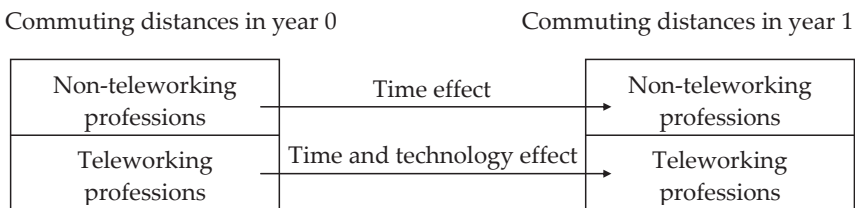
Expression (4) is identical to (1) for year  $t = 1$ . Figure 5.1 outlines the method's idea graphically.

One might decompose the average treatment effect (on the treated professions), as defined by (4) into two (non-causal) parts. By construction, this effect is the sum of the change in distance for employees in teleworking professions who are involved in teleworking plus the change in distance for employees who also work in these professions but do not telework. So, a straightforward accounting identity holds:

$$(5) \quad E[Y_1|d_1 = 1; t = 1] - E[Y_1|d_1 = 0; t = 1] = s\alpha_1 + (1 - s)\alpha_0$$

where  $s$  is the share of non-teleworking employees within teleworking professions,  $\alpha_1$  is the effect of technology on commuting distance of teleworkers within teleworking professions,  $\alpha_0$  is the effect for non-teleworkers within teleworking professions. It is difficult to identify the causal effect of technology adoption on commuting distances of teleworkers and non-teleworkers in teleworking professions, as we do not observe the relevant counterfactuals. Apart from the potential nontrivial measurement error of distinguishing teleworkers and non-teleworkers within teleworking professions, it might be that some individuals self-select themselves into longer commute based on certain unobserved characteristics, for example, they own a larger house, where they can telework more productively as they have a special office room. We do not know how their commuting distance would have changed over time if they would not have been exposed to the technology, although the knowledge of the magnitude of the technology effect on individuals is relevant for policy-making. In this empirical exercise we think this is hardly a problem for the estimation of the average effect of technology on commuting for the entire profession, as the

**Figure 5.1.** Identification strategy



unobserved characteristics do not correlate across a large set of professions which we aggregate into two types – teleworking and non-teleworking one.

### 5.2.2 Inference

We emphasize that we match observations from years 0 and 1. So, we aim to find comparable employees *within* both types of professions in years 0 and 1. Let us first focus on employees in teleworking professions. Our method must create a counterfactual of average distance of these employees, i.e., the average distance if none of these employees had adopted technology. This is achieved by estimating the employee's probability of being exposed to the technology based on observed socio-demographic and job-related employee characteristics. So, we compute the probability of an individual to be exposed to teleworking technology, i.e., to be observed in year 1, the so-called propensity score. Conditional on this score, whether individuals have been exposed to teleworking technology is assumed to be random.<sup>48</sup> This assumption allows for an inference of the causal effect of interest in a similar fashion to a randomized experiment.<sup>49</sup> We use kernel matching and match a treated employee (in year 1) with control employees (in year 0) who are within the kernel bandwidth, by weighting proportionally to the difference between propensity scores, i.e., if a control observation has propensity score which is closer to that of a treated observation than the weight of such a control is larger (Caliendo and Kopeinig, 2008).<sup>50</sup> Effectively, we match a single person within teleworking professions in year 1 to a statistical composite of individuals in year 0 who work in teleworking professions. The same procedure applies for employees in non-teleworking professions. Given the two matching estimations (for teleworking and non-teleworking professions), we calculate the average commuting distances of the matched groups in years 0 and 1 and then estimate expression (2) to obtain the causal effect of teleworking technology on commuting distance.

A similar methodology, sometimes referred to as “difference-in-differences in combination with matching” has been applied in the labor and international trade literature (Girma and Gorg, 2007; Arnold and Javorcik, 2009;

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<sup>48</sup> We formally test the balancing property of the matching to insure that observations in two matched groups are similar in observed variables.

<sup>49</sup> For an overview of the method and its limitations we refer to Dehejia and Wahba (2002), Angrist and Pischke (2008) and Caliendo and Kopeinig (2008).

<sup>50</sup> We will perform robustness checks with respect to the matching procedure.

Stiebale and Trax, 2011; Hijzen et al., 2013). This methodology follows individuals (or firms) over time. Thus, two comparable individuals are defined to be the same person in years 0 and 1. This approach provides the sum of the effect of teleworking technology and an age cohort effect and since the latter might be non-negligible, as we focus on a long time gap between both years, this approach is not preferable in our context.<sup>51</sup>

### 5.3 Empirical analysis

#### 5.3.1 Data

Our main data source provided by Statistics Netherlands is the cross-sectional Dutch Labor Force Survey for the years 1996 and 2010 which refer to years 0 and 1 in the discussion above. The dataset contains information on socio-demographic and job-related characteristics of 74,235 individuals (38,179 and 37,122 for 1996 and 2010, respectively).<sup>52</sup> We have information on a person's age, gender, marital status, education level, household size and composition, country of origin and municipality of the residential and job location. We also know employment status, total number of hours worked per week, whether a person has a fixed job contract, number of working hours, number of overtime hours, whether one manages subordinates, number of workers of the establishments, and job and industry type (as classified by Statistics Netherlands). We refer to Table 5.A in Appendix for descriptive statistics.

Commuting distance is measured based on the centroids of the residential and workplace municipalities. There are around 400 municipalities in the Netherlands. The commuting distance is assumed to be zero for persons who work and live in the same municipality (about 43% of employees in 1996 and 2010).<sup>53</sup> One-way average commuting distances were 10.1 km and 12.4 km in, respectively, 1996 and 2010.<sup>54</sup>

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<sup>51</sup> In case the cohort effect is not important or that it does not differ across teleworking and non-teleworking professions, panel data would be preferable.

<sup>52</sup> We consider employed individuals, between 18 and 64 years, working more than 12 hours per week, with a one-way commute distance of less than 100 km.

<sup>53</sup> When changes of distance within municipalities are in the same direction as changes across municipalities, which is plausible, our estimates of changes of commuting distances over time will be an underestimate.

<sup>54</sup> Self-reported average commuting distance in the Netherlands is 17 km over the period 2000–2008 (Groot et al., 2012). The difference with our data stems largely from within-municipality commutes that are assumed to be zero in our approach.

Respondents in 2010 answered a question about their *usual* workplace location.<sup>55</sup> We define a teleworker as an employee who answers that he or she performs some job tasks “at home” or “at home and at a location other than home”. In turn, a non-teleworker is a respondent who answers that he or she works “at locations other than home”. Our data contains 1,065 teleworkers (around 3% of all employees in the data), of whom 85 work exclusively from home. Other employees will be labeled as non-teleworkers. We do not have information on the number of days that they telework. So, we measure the extensive margin of teleworking.<sup>56</sup> No information on teleworking is available for the year 1996. Given the low penetration level of the Internet in the Netherlands in this year, it seems reasonable to assume that teleworking technology was not available to workers in any profession. This is not essential: if some employees have adopted technology in 1996, then our results show the effect of the change in technology between 1996 and 2010.

### 5.3.2 Teleworking and non-teleworking professions

We start with an identification of teleworking professions in 2010, i.e., professions in which teleworking is (relatively) widespread, and non-teleworking professions, where it is completely absent. We have detailed information about the employee’s job and industry types. We define a profession as a particular job within an industry at an aggregated classification level of 9 job types and 45 industry types, so we distinguish between 405 professions.<sup>57</sup> The distribution of shares of teleworkers within professions is given in Figure 5.A in Appendix.

We define a profession to be a teleworking one if more than 5% of employees in this profession telework in 2010.<sup>58</sup> A profession is a non-teleworking one if none of its employees telework in 2010. A profession is defined as a limited teleworking profession if the share of teleworkers is

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<sup>55</sup> The original question in the Dutch language is “Waar werkt u in deze werkkring doorgaans?”, which one might translate as “Where do you usually work on this job?”. This question in the survey is clearly distinguished from another question about instances of overworking at home.

<sup>56</sup> For an overview on the measurement of teleworking we refer to Sullivan (2003).

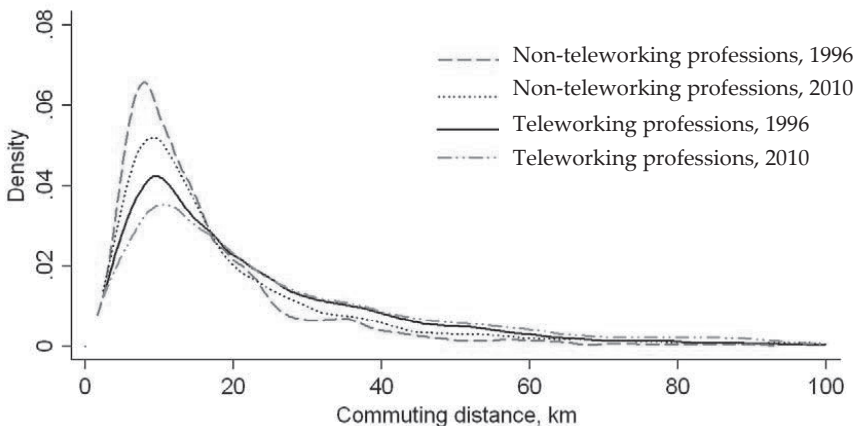
<sup>57</sup> In choosing the scale of aggregation one has to trade off homogeneity of the resulting groups with the availability of the observations in order not to classify each employee as a single representative of a profession.

<sup>58</sup> As a robustness check, we also provide results that are derived for a cut-off value of 10%.

positive but below 5%. The latter group is left out of the analysis, as the effect of the technology on commuting distance, which we try to identify, is the most pronounced in the professions with high adoption rate of teleworking. Inclusion of the limited teleworking professions would bias our diff-in-diff result to zero, as professions are likely to have a substantial measurement error (which would strongly affect limited teleworking professions), since our definition of teleworking and non-teleworking professions are based on finite (and sometimes small) samples. In a limiting case when professions are randomly assigned into teleworking and non-teleworking groups the diff-in-diff is zero. To reduce this bias, we exclude professions for which we have less than 10 observations (less than 1% of employees in both teleworking and non-teleworking professions). We are then left with 105 professions of which 35 are defined as teleworking. Our analysis is then based on 5,699 (6,756) and 5,662 (5,505) employees in, respectively, non-teleworking and teleworking professions in 2010 (1996). In the teleworking professions we observe 427 teleworkers.

Our identification strategy is based on changes over time in commuting distance. Figure 5.2 shows distributions of commuting distances for teleworking and non-teleworking professions in 1996 and 2010 for workers that

**Figure 5.2.** Commuting distances in 1996 and 2010



Notes: Distances are shown only for employees who commute between different municipalities



commute between different municipalities.<sup>59</sup> Figure 5.2 suggests that changes in commuting distances over the 14 years across professions were roughly in the same direction and magnitude. For example, the share of employees who commute long distances (i.e., 20 km and more) is higher in teleworking than in non-teleworking professions in both years.

Employees in teleworking and non-teleworking professions account for 15.4% and 15.5% of all employees in 2010, not very different from 14.5% and 17.8% in 1996.<sup>60</sup> The average commuting distance for teleworking professions has grown by 2.8 km from 15.1 (in 1996) to 17.9 km (in 2010). For non-teleworking professions, the average commuting distances has grown by 2.6 km from 7.4 (in 1996) to 10 km (in 2010).

The long-run causal effect, as defined by (2), can be estimated using the changes over time in average commuting distance for both profession types. When we ignore changes over time in socio-demographic and job-related characteristics (which we will account for later on using matching), this effect is equal to  $2.8 - 2.6$ , so 0.2 (with a standard error of 0.4). This suggests that there is no effect of technology adoption on average commuting distances. We now use propensity score matching to account for changes in characteristics over time.

### 5.3.3 Results

Table 5.1 shows logit estimates for a model that estimates the probability that an employee is observed to work in 2010. We estimate the model separately for employees in teleworking and non-teleworking professions. In both profession types, employees in 2010 are, on average, older, more likely to be females, belonging to a larger household, working less hours but working more overtime than in 1996.

The implied probabilities of Table 5.1 are taken as propensity scores to match employees from 1996 with those from 2010.<sup>61</sup> We apply non-parametric kernel matching with replacement such that the means of the standardized biases across covariates for the two matched groups are minimized (see

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<sup>59</sup> Commuting within a municipality occurs in 49% (54%) and 31% (33%) in 2010 (1996) of, respectively, non-teleworking and teleworking professions.

<sup>60</sup> So, the majority of employees work in professions in which limited teleworking occurs.

<sup>61</sup> For the propensity score matching estimates (and subsequent testing of the results), we use the “psmatch2” and “pstest” commands in Stata, developed by Leuven and Sianesi (2012).

Caliendo and Kopeinig, 2008).<sup>62</sup> We have investigated the sensitivity of the results in various ways with respect to specification and matching procedure.<sup>63</sup> There are very few, less than 1.5%, off-support observations from the total number of observations in year 2010 (80 and 84 in, respectively, teleworking and non-teleworking professions). Off-support observations are those that have propensity scores that are not found among control group observations. Off-support observations in 2010 are not matched with control observations in 1996 and are discarded from the further analysis.

Table 5.2 shows balancing tests by comparing the mean values of covariates across unmatched and matched groups. For example, for the variable “age”, the first row shows the mean values of age in the unmatched sample both in 2010 and 1996 and the difference between the two, indicated by a

**Table 5.1.** Logit estimates whether an employee works in 2010

	Non-teleworking professions		Teleworking professions	
	coefficient	SE	coefficient	SE
Age	0.0909***	(0.0031)	0.0662***	(0.0032)
Male	-0.1563**	(0.0607)	-0.4706***	(0.0613)
Foreign-born	0.3194***	(0.0777)	0.2682***	(0.0917)
Household size	0.3043**	(0.1400)	0.5352**	(0.2611)
Hours of work	-0.0204***	(0.0030)	-0.016***	(0.0042)
Hours of overwork	0.0528***	(0.0063)	0.2362***	(0.0092)
Fixed contract	-0.4980***	(0.0698)	-0.0090	(0.088)
Fixed hours	-1.0581***	(0.1263)	-0.9731**	(0.3761)
No other co-workers	-3.2128***	(0.2185)	-3.6987***	(0.3056)
Managerial position	0.4687***	(0.0645)	-0.3274***	(0.0528)
Number of observations	12.455		11.167	
Pseudo R <sup>2</sup>	0.3386		0.2944	

Notes: \*\*p<0.05, \*\*\*p<0.01. These estimates also control for industry type (44), job type (8), education level (5), household type (5), marriage status (4), number of employees in establishment (6), number of children (5), country's region (4).

<sup>62</sup> The standardized bias is defined as the percentage difference of sample means in the treated and matched control subsamples as a percentage of the square root of the average of sample variances in both groups (Caliendo and Kopeinig, 2008; Leuven and Sianesi, 2012).

<sup>63</sup> For example, we have included interaction and higher order terms, excluded some variables, applied a more restrictive definition of teleworking professions. We have also applied other matching procedures such as one-to-one, three-to-one and five-to-one neighbors, and caliper, and have varied the kernel bandwidth.

**Table 5.2.** Balancing tests

Variable	a	Non-teleworking professions				Teleworking professions			
		Mean value		Bias <sup>b</sup>	Bias reduction	Mean value		Bias <sup>b</sup>	Bias reduction
		2010	1996			2010	1996		
Age	U	38.6	34.4	34.8		40.2	37.1	30.7	
	M	38.5	37.7	6.7	80.7	40.1	38.9	12.0	60.9
Male	U	0.554	0.588	6.8		0.66	0.71	-11.2	
	M	0.554	0.553	0.2	96.5	0.66	0.64	4.4	61.3
Foreign-born	U	0.13	0.1	9.4		0.08	0.06	7.7	
	M	0.13	0.17	13.0	-38.2	0.08	0.09	-2.9	61.9
Household size	U	3.08	2.98	7.2		2.99	2.87	10.1	
	M	3.08	3.09	0.8	88.3	2.99	3.04	-4.0	60.0
Hours of work	U	31.1	33.7	27.7		36.56	37.6	-15.7	
	M	31.2	31.8	6.5	76.4	35.84	36.5	10.1	35.7
Hours of overwork	U	1.68	1.00	16.6		3.46	0.56	59.6	
	M	1.66	1.90	-6.0	64.0	3.09	4.47	-28.0	53.1
Fixed contract (binary)	U	0.81	0.87	-16.6		0.91	0.91	0.4	
	M	0.816	0.78	10.7	35.6	0.911	0.89	4.8	-1179.6
Fixed hours (binary)	U	0.91	0.98	-31.3		0.99	1.00	-10.9	
	M	0.92	0.93	-6.1	80.4	0.99	0.99	-0.9	91.5
No other co-workers	U	0.01	0.02	-4.1		0.01	0.01	1.8	
	M	0.01	0.01	0.7	81.9	0.01	0.01	-0.2	90.8
Managerial position	U	0.22	0.14	19.9		0.42	0.42	-0.5	
	M	0.22	0.20	4.2	78.9	0.41	0.35	12.6	-2314.1
Mean standardized bias	U			8.8				10.5	
	M			2.8				5.1	

Notes: <sup>a</sup> U – unmatched, M – matched<sup>b</sup> Mean standardized bias without and with matching, see Rosenbaum and Rubin (1985)

standardized bias which is often used in the literature. The second row shows the same information for the matched samples and the reduction in the bias, which is due to the matching procedure. We examine whether different groups have the same covariate means (see Rosenbaum and Rubin, 1985).

For non-teleworking professions, the mean standardized bias across the covariates is reduced from 8.8 to 2.8 due to matching, whereas for teleworking professions, it is reduced from 10.5 to 5.1. So, for both professions the reduction

is substantial. These values indicate successful matching, insuring similarity of treatment and control groups (Caliendo and Kopeinig, 2008).

Table 5.3 presents the main result for the matched employees. The average commuting distance in non-teleworking professions has grown by 2.3 km (with a standard error of 0.51) from 7.7 in 1996 to 10 km in 2010. The average commuting distance in teleworking professions has grown by 1.98 km, with a standard error of 0.76, from 15.8 km in 1996 to 17.8 km in 2010. The difference-in-differences estimate is then equal to -0.32 with a standard error of 0.92 (the diff-in-diff estimate given matching is close to this estimate for the unmatched samples which is 0.20). This implies that we cannot reject the hypothesis that changes in commuting distance over time for both teleworking and non-teleworking professions were statistically identical.

Let us now focus on employees in teleworking professions only, and distinguish between teleworkers and non-teleworkers. We then repeat the entire analysis for teleworkers and non-teleworkers within these professions separately. Such an analysis provides the (non-causal) change in commuting distances over time. In Table 5.4 we observe that teleworkers increased their commuting distance by 12.07 km, while non-teleworkers in teleworking professions have increased their commuting distance by only 1.32 km,

**Table 5.3.** Commuting distance, *causal effect*

	Employees in		Diff	SE	Diff-in-diff	SE
	1996	2010				
Teleworking professions	15.82	17.80	1.98	(0.76)	-0.32	(0.92)
Non-teleworking professions	7.70	10.00	2.30	(0.51)		

**Table 5.4.** Commuting distance within teleworking professions, *non-causal effect*

	Employees in		Diff	SE
	1996	2010		
Teleworkers	14.45	26.52	12.07	(2.56)
Non-teleworkers	16.13	17.45	1.32	(1.24)

which is less than the increase of 2.3 of non-teleworkers in non-teleworking professions (see Table 2). We emphasize again that this effect is non-causal: it maybe those individuals who have a long commute choose to telework.

In light of the result from Table 5.3, which shows that the diff-in-diff estimator is not statistically significant, the large difference between commuting distances for teleworkers and non-teleworkers suggests that the spatial commuting pattern of employees in teleworking and non-teleworking professions is, at least in part, governed by sorting, in which employees who already live further away from work choose to adopt teleworking.<sup>64</sup>

#### 5.4 Sensitivity analysis

Table 5.5 shows that our main result is robust with respect to various matching procedures and it also holds if we restrict the samples of observations. We perform neighbor one-to-one, with and without replacement matching, which allow to check whether our result is driven by the subset of 1996 observations that are disproportionally often matched to 2010 observations. The main result remains the same. We also restrict the sample of employees in 2010 to those older than 40 years because older employees are less likely to have chosen their profession given the possibility of teleworking, which would upward bias our estimate due to sorting. If we assume that the within-municipality commute is 3 km, instead of being 0 km, we obtain similar results. To check whether our results are driven by a few teleworking professions which have a lot of employees, we include only professions that have less than 600 employees in our dataset.

Finally, we repeat the entire analysis for the limited teleworking professions group to confirm that the average effect of adoption of the technology, for the workers in this profession group, is not larger than for the teleworking professions. In all these cases the diff-in-diff estimator remains

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<sup>64</sup> To check whether diverging effect of adoption of teleworking technology on average commuting distance might be driven by the relocation of firms away from central urban locations towards cheaper locations to save on land rents, we studied changes over time in urbanization patterns for two profession types. We have repeated the entire exercise and used as a dependent variable not the commuting distance, but the measure of urbanization (ratio of residents over employees in municipality of employment). The results (not reported here) show no difference in changes over time across profession types. This does not go in line with the hypothesis of teleworking firms relocation due to technology adoption.

statistically insignificant. Importantly, in a few specifications the alternative estimator has a lower standard error, but even then the coefficient is not significant.

**Table 5.5.** Robustness checks of matching results for commuting distance

N(1) matching with replacement	Employees				Diff-in- diff	SE
	1996	2010	Diff	SE		
Teleworking professions	16.40	17.80	1.40	(1.12)	-0.92	(1.34)
Non-teleworking professions	7.69	10.00	2.32	(0.73)		
N(1) matching without replacement						
Teleworking professions	15.06	17.70	2.65	(0.37)	0.26	(0.46)
Non-teleworking professions	7.62	10.00	2.39	(0.27)		
Only employees above 40 years in 2010						
Teleworking professions	16.13	18.21	2.08	(1.25)	1.35	(1.49)
Non-teleworking professions	9.11	9.84	0.73	(0.81)		
Intra-municipality commute of 3 km						
Teleworking professions	16.72	18.71	1.99	(0.73)	-0.15	(0.87)
Non-teleworking professions	9.34	11.48	2.14	(0.48)		
No large teleworking professions						
Teleworking professions	17.72	18.86	1.15	(0.93)	-1.15	(1.06)
Non-teleworking professions	7.70	10.00	2.30	(0.51)		
10% cut-off threshold for teleworking professions						
Teleworking professions	22.37	23.28	0.91	(2.74)	-1.39	(2.78)
Non-teleworking professions	7.70	10.00	2.30	(0.51)		
Limited teleworking professions (0%–5%)						
Limited teleworking professions	9.38	11.69	2.31	(0.14)	0.01	(0.58)
Non-teleworking professions	7.70	10.00	2.30	(0.51)		

## 5.5 Conclusions

In this chapter we estimate a long-run causal effect of the adoption of teleworking technology on commuting distances. To estimate this effect, we apply a difference-in-differences method which exploits variation in

teleworking technology adoption between 1996 and 2010 and across professions. We distinguish between teleworking professions, where at least 5% of workers are involved in teleworking, and non-teleworking professions where no one of the workers teleworks. The latter group provides control estimates of how commuting distances change over time when no adoption to technology is present. The former group should reveal the causal effect of technology. To account for time changes in observable covariates, we apply a propensity score matching procedure. Our key identification assumption is that the difference over time between changes in the average commuting distances of these professions is solely due to the teleworking technologies.

Our results show that a long-run causal effect of technology on commuting distance is absent. Furthermore, we find that non-teleworkers in teleworking professions decreased their commute between 1996 and 2010 compared to workers in non-teleworking professions. The latter fact appears not easy to explain, as the urbanization patterns of the profession types have changed over time in the same manner. This implies that the difference in relocation of teleworking firms as compared to relocation of non-teleworking ones is not the driving force behind the result of irresponsiveness of commuting distances. A strong sorting effect seems to matter much more. From a policy point of view, our result suggests that teleworking might be a suitable second-best tool to tackle the negative externalities of transportation, as second-order spatial effects do not counterweight the positive effects of commute reduction.

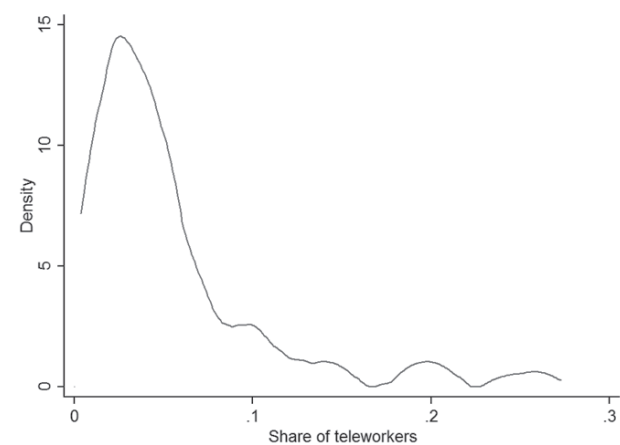
## Appendix

Table 5.A. Descriptive statistics

Variables	1996	2010	
	non-teleworkers	non-teleworkers	teleworkers
One-way commuting distance (km)	12.0	13.8	22.1
Age	36.9	40.6	43.2
Males (percent)	59.5	51.8	62.9
Born outside the Netherlands (percent)	7.3	9.6	6.1
Household size	3.0	3.0	3.1
Married (percent)	61.4	58.9	65.5
Children (age range)			
0 – 5	27.5	24.4	27.2
6 – 11	23.6	25.1	29.7
7 – 12	25.3	32.5	37.6
18+	32.0	27.3	36.8
Education level			
NA	5.8	1.2	0.0
School education	22.4	14.8	5.5
Middle-level applied education	40.3	41.3	29.6
Higher professional education	5.0	3.3	2.4
Higher education	26.5	39.4	62.5
Fixed contract (percent)	89.6	87.2	93.2
Fixed hours (percent)	99.2	96.0	97.4
Total working hours per week	34.9	32.6	35.4
Hours of overwork per week	0.8	2.2	5.5
Managerial position (percent)	25.4	27.0	42.6
Number of coworkers (percent)			
2 – 9	9.1	5.6	5.0
10 – 19	6.9	6.4	5.9
20 – 49	10.4	11.1	13.7
50 – 99	9.4	9.7	11.3
100+	61.7	37.0	43.7
NA	2.5	30.2	
Number of observations	38,179	36,056	1,066



**Figure 5.A.** Share of teleworkers within professions in 2010



Note: The share of professions with no teleworkers is 0.53

## 6 Conclusions

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### 6.1 Summary

Four research chapters included in this dissertation analyze how changes in individuals' travel behavior induced by information technologies affect social welfare. Chapters 2, 3 and 4 develop stylized microeconomic models which are largely set within the frameworks of transport and urban economics, and economics of industrial organization. Chapter 5 is an econometric exercise that uses an extensive dataset at the individual level. Several types of information technology are considered, encompassing both substitutes for and complements to traveling. Chapters 2 and 5 study telework-enabling technology that facilitates out-of-office work arrangements, while traffic information for drivers that supports efficient travel choices is examined in Chapter 4. First-best road tolling, varying over time of day, is the focus of Chapter 3. Given the important role that technology plays in the practical implementation of road pricing, such an analysis also provides insights into the social welfare consequences that technology-enhanced solutions to transportation problems might have.

This thesis contributes to the existing literature in three ways. Firstly, it proposes novel ways of investigating, from an economic perspective, the relationship between information technologies and travel behavior. Chapter 2 incorporates into Vickrey's (1969) microeconomic equilibrium model of dynamic road bottleneck congestion an analysis of the behavioral and welfare impacts of a teleworking technology. Chapter 3 combines Vickrey's bottleneck model and the monocentric city model, and analyzes individual travel and location behavior when travel and residential location choices are mutually dependent. Chapter 4 analyzes equilibrium and welfare in a market where the road operator and the traffic information provider are independent, and can be public or private.

Secondly, Chapter 5 provides an empirical contribution to the economic literature, by suggesting an identification strategy for the estimation of a causal long-run effect of teleworking technology adoption on commuting distances and, indirectly, on negative travel externalities. We combine data from a large labor force survey from a period before information technology became

widespread and a period when Internet is ubiquitous. This offers an interesting way to addressing a potential reverse causality problem of endogenous technology access.

Thirdly, the findings reported in this thesis may help policy makers to promote theoretically sound measures to tackle long standing transportation problems. The results of the thesis help to be aware of the economic consequences, both desirable and not, of novel transport policies. A brief overview is as follows.

Chapter 2 studies the potential equilibrium and welfare effects of teleworking for congested road commuting. Teleworking is broadly defined as an out-of-office work arrangement where an employee can perform some of the job tasks from home. Unlike the majority of the existing studies that analyze the economic effects of whole-day teleworking, this chapter focuses on the travel impacts of - empirically relevant - part-day teleworking. This means that an employee might work from home for a few hours in the morning to avoid peak period congestion. The analysis is cast in the framework of Vickrey's (1969) dynamic bottleneck model, which allows analyzing the individuals' departure time choices as an outcome of trade-offs between the opportunity costs of spending time at home, work and in a vehicle. The possibility to work from home due to the teleworking-enabling technology, such as Internet and computers, translates in a higher marginal utility of spending additional time at home, and thus changes the travel trade-off that a person faces.

It turns out that an individual who is equipped with teleworking-enabling technology tends to postpone the commute, and to depart from home later than she would otherwise do. While it is beneficial for the teleworker, it might also be welfare improving for unequipped drivers who face weaker congestion. However, the larger the number of drivers who telework and postpone their commute in the same manner, the more the congestion peak period shifts to a later time period. Social benefits from a dispersion of preferences may then decrease in the number of teleworkers. This result shows that, in absence of optimal congestion pricing, there is an optimal level of technology penetration above which teleworking technology, even if it is free-of-charge, might be socially detrimental. Due to this, private monopolistic supply of the technology, albeit restrictive, might yield a higher social welfare than perfectly competitive supply.

Chapter 3 analyses the longer run economic interactions between commuting, including the scheduling of commuter trips, and urban development. This chapter attempts to merge, for the first time, Vickrey's bottleneck model and the monocentric city model in which both scheduling and location choices influence each other. The new model considers a monocentric city where a traffic bottleneck is located at the entrance of the central business district. The commuters' departure times from home, residential locations, and lot sizes, are all endogenous.

The results show that the elimination of queuing time under optimal road pricing induces individuals to spend more time at home and therefore to have larger houses, thus causing urban sprawl in the long run. This is opposite to the typical results of urban models with static congestion, which predict cities to become denser with road pricing. To reach this conclusion the model considers how the amount of time that drivers spend at home and in the car changes due to the introduction of congestion pricing. Because drivers would no longer spend time waiting in the car, the amount of time spent at home increases. An important assumption that the model introduces is that, if everything else is constant, the larger the house one lives in, the more benefit one derives from spending additional time in it. Thus, when a driver spends more time at home in the morning, he or she has a stronger demand for a larger house. While this effect might be relatively small at an individual level, over the long term for the entire city it might be noticeable. Despite the difference with findings in static models, the result is in another sense in line with previous studies that show that improved urban transportation, such as availability of extended road capacity or cheaper modes of transportation, causes urban sprawl as well.

Chapter 4 considers welfare effects of traffic information provided to drivers. While both private and public firms might inform drivers about traffic conditions, it is not clear to what extent these arrangements are socially beneficial in a market where a separate firm operates a road network. This chapter uses a simple microeconomic model of elastic travel demand and stochastic travel cost to derive an endogenous demand for traffic information. Profit-maximizing pricing strategies of the information provider and road operator depend on each other as both road toll and price of traffic information affect the number of drivers making a trip, and thus the market size that can generate profit.

It appears that the distortive welfare effect of monopolistic information provision is relatively small. The main pricing strategy of the information provider is to appropriate the (constant) consumer surplus of drivers who travel even when the travel costs are high. The monopolistic mark-up redistributes surplus from the consumers to the information monopolist, but does not crowd many drivers out of the market. The results show that a cooperating road operator and traffic information provider offer a lower joint price compared to the case where these companies operate separately, because their profits are interrelated. The mechanism behind this is closely related to the regular argument in models of double marginalization, albeit that now both firms sell directly to consumers and the two goods are not strictly complementary: one could travel without having the information. There appears little reason to prevent private road operators from offering information on traffic conditions on their roads.

Chapter 5 returns to the topic of teleworking and examines its spatial consequences empirically. Despite strong policy support for teleworking, economists raise concerns that if commuting becomes less expensive due to teleworking, an employee might change the residential location to a (cheaper) place further away from the workplace. Additional kilometers traveled, although less frequently, could potentially offset the positive effects of teleworking on, for example, congestion and air pollution. This chapter checks whether within professions where many people telework, average commuting distance is affected by the technology. The identification strategy of chapter 5 tests this assertion while taking care of the reverse causality problem of endogenous technology availability, by applying a difference-in-differences method in combination with propensity score matching. Cross-sectional Dutch labor force survey data from 1996, when technology was barely present, and 2010, when Internet was pervasive, provides a way to estimate the long-run casual effect of the adoption of teleworking practices on the length of commuting distances.

The results indicate that average commuting distances have increased over time by 2 km for professions where substantial share of employees telework. The same increase took place over time in the professions where no one teleworks. This implies that the adoption of teleworking technologies does not affect average commuting distances. The results also suggest that there is a divergent effect of technology on teleworkers and non-teleworkers within

teleworking professions. While teleworkers would still have a longer commute, on average it is counterweighted by the reduction of commuting distances for non-teleworkers, as compared to non-teleworkers in non-teleworking professions. This puzzle warrants an explanation which appears difficult to pinpoint.

## 6.2 Policy implications

This thesis shows that information technologies provide intriguing possibilities to improve transportation, either through reducing the generalized costs of travel or decreasing the demand for travel altogether. Several policy implications follow from the research results.

Second-best solutions to transport problems should be applied with certain caution, as they may produce unanticipated effects. In general, road congestion arises when too many people at the same place and at the same time want to pass through a road with limited capacity. One way to resolve congestion problems is to spread the incoming flow of vehicles, either over space or over time. Part-day teleworking induces drivers to reconsider their departure time decisions and avoid peak period travel by traveling later. However, if too many people decide to behave the same way, the queues may become longer in a different time period. While current levels of teleworking might not be high enough for this problem to become pressing, an efficient policy should account for this effect in the future when endorsing teleworking in the hope to fight congestion.

Traffic congestion is a predominantly urban problem, especially the one of a recurrent nature that often happens during morning and evening commute hours. It has been known from earlier work that transportation costs affect urban structure, and this fact has been reconfirmed in this thesis. Importantly, a more realistic consideration of congestion by accounting for its dynamic nature, shows that improvements of transportation by imposing first-best road pricing may increase city size and welfare, like the construction of larger transport capacity or the provision of cheaper transport modes would. This might give another reason for urban transport authorities to support congestion pricing as a policy tool to tackle congestion.

Travel-complementary information technologies, such as traffic information to drivers, seem to be a popular way of achieving transportation

improvements. The results of this thesis suggest that the private provision of traffic information is a feasible and relatively efficient way of achieving social benefits from such technologies, as abuse of monopolistic market power does not lead to large forgone economic activities as is usually the case in monopolistic markets. Traffic information firms should be encouraged to provide their services even if they cooperate with road operators, private or public.

Finally, this thesis also finds that spatial effects due to teleworking technologies are not present at aggregate levels of professions, implying that teleworking does not aggravate negative travel externalities through spatial second-order effects. This suggests that policy makers might feel more comfortable with the promotion of teleworking as a suitable tool to fight negative travel externalities than what would be warranted if such effects would have been found.

### 6.3 Future research

As long as technological progress continues, there will always be a need for analysis of its economic implications for informed policy making. It goes without saying that richer versions of the models presented in this thesis would shed more light on the effects of technology. For example, chapter 2 might benefit from considerations of initial heterogeneity, in terms of preferred arrival times, values of schedule delays, and benefits from teleworking. Such extensions, however, pose analytical challenges as the order of arrivals at work might change for equipped drivers, which make derivation of closed form solutions a tedious endeavor. Another way to extend the model could be to incorporate a positive network effect to account for the fact that the larger the number of teleworkers are, the more beneficial the technology may become to its users, due to higher productivity that a teleworker may attain if other employees telework as well.

Several modifications of a spatial bottleneck model from chapter 3 may be particularly attractive. The first is to generalize the model to allow drivers to arrive at work late. The second is the change of the utility structure from a standard piece-wise linear (" $\alpha$ - $\beta$ - $\gamma$ ") to continuous upward and downward sloping one (" $H$ - $W$ "), which may strengthen the model by leaving out assumption 1 (Kim and Fosgerau (2014) are currently following this path).

Indeed, assumption 1, which states that the larger the house is the more utility an individual drivers from spending additional time in it, is a call for empirical check. One way of validating or rejecting this assumption would be to consider house characteristics of drivers in relation to their arrival times during peak period congestion. That is, if drivers living in large houses, everything else constant, would arrive at the back of the bottleneck relatively late, this would be consistent with the assumption. This analysis would require detailed data on residential and travel behavior of drivers.

An interesting extension of the industrial organization model of chapter 4 would be to include the possibility of congestion, which links marginal cost of travel with the number of drivers on the road. Consideration of information imprecision, when the quality of information in some way is not perfect, e.g., by introducing probability values of whether information provided is correct or not, may be another way of extending the model.

This closing section seems suitable also for a brief contemplation on other technological advances that transportation might soon face. Among many such advances, driverless cars and car sharing seem to be ones of the most interesting, as they have potential ability to change the way transportation functions.

Technology that would allow driverless cars to be part of traffic flows seems to develop very quickly. Chapter 2 models teleworking as an increase in utility of spending time at home. In a similar fashion driverless cars might yield higher utility of spending time in a vehicle. This modeling approach could offer a straightforward way of incorporating such a new technology into the analysis of drivers' behavior during congestion, and can bring useful insights. Another way of looking at driverless cars would be to consider changes in the urban structure that such a technology might bring (maybe within the framework of the monocentric city model). To give an example, overnight parking of driverless cars may be possible at locations away from residential places and closer to the city fringe, unlike in the case of the conventional cars which are usually parked right next to the drivers' homes. The underlying reason why a driver would want to park her car away from the residence location is the monetary gains from a cheaper rent for a parking lot that a driver pays if the parking lot is closer to the city fringe. Disentangling of parking space away from expensive residential locations further to the city fringe may profoundly change city size, density and welfare.



The networks of car sharing arrangements is another innovation that may strongly affect the way people travel as car sharing becomes increasingly popular largely due to the enhanced convenience that information technologies bring to such services. Whether negative travel externalities such as air pollution or congestion could be tackled, is unclear. It may be interesting to consider, in the spirit of chapter 4, whether and to what extent private or public provision of such services is justified.

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## Nederlandstalige samenvatting (summary in Dutch language)

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Reizen is in de afgelopen eeuwen sneller, veiliger, comfortabeler, betrouwbaarder, efficiënter in het gebruik van energie, maar bovenal, veel goedkoper geworden. Deze ontwikkelingen werden vooral veroorzaakt door de vooruitgang van de wetenschap en techniek. De meer recente opkomst van informatietechnologie draagt verder bij aan deze ontwikkelingen door, bijvoorbeeld, moderne satelliet gestuurde navigatiesystemen waardoor automobilisten efficiënter en met minder stress complexe routes kunnen volgen. De technologie zal zich ook blijven ontwikkelen in de toekomst. Dit proefschrift draagt bij aan een betere kennis van de economische gevolgen van deze technologische ontwikkelingen en aan een betere onderbouwing van het hedendaagse transportbeleid.

Door de toename van de bevolking en de welvaart van huishoudens is zowel het aantal verplaatsingen als de gemiddelde lengte van verplaatsingen sterk toegenomen in de laatste jaren. Hierdoor nemen de uitgaven aan vervoer een belangrijk deel van het huishoud- en tijdbudget in, en spenderen overheden een substantieel deel van de belastinginkomsten aan infrastructuur. Ondanks de ontwikkelingen op dit gebied van de afgelopen eeuwen, spelen er nog steeds problemen op het gebied van vervoer en infrastructuur die sterk lijken op de problemen van honderd jaar geleden. Milieuoverlast veroorzaakt door grote hoeveelheden paardenmest is vervangen door zorgen over luchtvervuiling en geluidsoverlast. Congestie is de afgelopen decennia toegenomen en verkeersveiligheid blijft een punt van zorg. Privatisering van transport- en vervoersfaciliteiten, en regulering van private transportbedrijven wakkeren vaak felle publieke debatten aan omdat de uitkomsten van dergelijke maatregelen niet altijd goed te voorspellen zijn, en voor sommige partijen positief maar voor andere partijen negatief uit kunnen pakken. Alhoewel technici, stadsplanners, maar ook economen, hebben bijgedragen aan een verbeterde efficiëntie van transport, blijven de aanhoudende uitdagingen vragen om innovatieve oplossingen.

In dit proefschrift wordt, vanuit een economische invalshoek, een aantal intrigerende beleidsmaatregelen ten aanzien van vervoer en transport onderzocht die samenhangen met de opkomst van informatietechnologie zoals het internet, draadloze communicatie en efficiëntere realtime meetmogelijkheden. De keuze voor de beleidsmaatregelen die in dit proefschrift worden onderzocht, zijn deels ingegeven door de aspiratie om eerder aangetoonde hiaten in de onderzoeksagenda op te vullen. Of, en onder welke omstandigheden deze technologie-gedreven maatregelen leiden tot maatschappelijk wenselijke veranderingen in reisgedrag van individuen is de kernvraag die in vier hoofdstukken in dit proefschrift onderzocht wordt.

In hoofdstuk 2 worden de effecten geanalyseerd van telewerken op de kosten van woon-werkverkeer als er sprake is van verkeerscongestie. Telewerken wordt gedefinieerd als een regeling waarbij de werknemer een gedeelte van zijn werktaken thuis kan uitvoeren. In tegenstelling tot de meeste onderzoeken die gericht zijn op de economische effecten van een volledige dag telewerken, is dit hoofdstuk gericht op de effecten van, het empirisch relevantere, telewerken per dagdeel op het woon-werkverkeer. Dit betekent dat een werknemer een gedeelte van de dag of een aantal uur in de ochtend thuis werkt om de ochtendspits te mijden. De mogelijkheden voor thuiswerken als gevolg van ondersteunende technologie voor telewerken, zoals computers en internet, beïnvloedt het nut dat een individu kan onttelen aan het spenderen van meer tijd thuis, wat van invloed kan zijn op de keuze van de vertrektijd om naar het werk te gaan.

Het blijkt dat een individu die de beschikking heeft over de technologie die telewerken mogelijk maakt, de neiging heeft om een latere vertrektijd te kiezen dan anders het geval zou zijn. Dit is niet alleen gunstig voor de telewerker, maar kan ook welvaart verhogend zijn voor weggebruikers die niet de mogelijkheid tot telewerken hebben omdat er minder congestie is. Echter, hoe groter het aantal weggebruikers dat kan telewerken en de reis naar het werk uitstelt tot een later tijdstip, hoe meer de ochtendspits zich verplaatst naar een later tijdstip. De maatschappelijke baten van de spreiding van preferenties kunnen dan afnemen als het aantal telewerkers toeneemt. Dit resultaat laat zien dat, bij de afwezigheid van een optimale congestieheffing, er een optimaal niveau is waarbij het gebruik van technologie voor telewerken wordt toegepast, en dat boven dit niveau, zelfs als er geen kosten aan verbonden zijn, het gebruik van telewerken maatschappelijk nadelig kan zijn. Hierdoor kan het aanbieden

van de technologie voor telewerken in een private monopolistische markt een hogere maatschappelijke welvaart opleveren dan het aanbod in een perfect competitieve markt, ook al levert dit restricties op.

Dit resultaat benadrukt dat *second-best* oplossingen voor transportproblemen met een zekere mate van terughoudendheid toegepast moeten worden omdat er onverwachte effecten kunnen ontstaan. In het algemeen ontstaat congestie in het wegennetwerk als te veel reizigers op hetzelfde moment op dezelfde plek over een weg met beperkte capaciteit rijden. Een oplossing voor congestie is om de toestroom van voertuigen te spreiden in termen van tijd of plaats. Telewerken per dagdeel leidt er toe dat reizigers de keuze van hun vertrektijd heroverwegen en de ochtendspits mijden door later te reizen. Echter, als te veel reizigers dezelfde overweging maken, kunnen de opstoppen op het wegennetwerk groter worden op een ander tijdstip. Alhoewel de huidige omvang van telewerken niet voldoende is om tot dergelijke problemen te leiden, moet efficiënt beleid rekening houden met deze toekomstige effecten bij het promoten van telewerken om congestie tegen te gaan.

In hoofdstuk 3 worden de langetermijn economische interacties tussen woon-werkverkeer, inclusief de keuze van het tijdstip van de reis, en stedelijke ontwikkeling geanalyseerd. In dit hoofdstuk wordt, als eerste in de literatuur, een economisch model gecreëerd waarin de tijdstipkeuze en locatiekeuze van individuen onderling afhankelijk zijn. In dit model wordt uitgegaan van een stad met een centraal gelegen zakenwijk, met daaromheen woonwijken. In het model wordt aangenomen dat de toegangsweg naar de zakenwijk een *bottleneck* is. De vertrektijd van werknemers, de woonlocatie, en de omvang van woningen worden endogeen in het model bepaald.

De resultaten van dit model laten zien dat de afwezigheid van congestie door optimale tolheffing er toe leidt dat werknemers meer tijd thuis besteden en daardoor grotere huizen hebben, waardoor steden zich uitbreiden op de lange termijn. Om tot deze conclusie te komen, is er in het model in hoofdstuk 3 gekeken hoe de hoeveelheid tijd die een werknemer thuis en in de auto besteedt, verandert bij de invoering van congestieheffingen. De tijd die thuis gespendeerd wordt neemt toe omdat werknemers geen tijd meer besteden in de file. Een belangrijke aanname die in het model wordt geïntroduceerd is dat, als alle andere factoren constant blijven, iemand meer nut ontleent aan de additionele tijd die thuis besteed wordt naar mate het huis waar iemand woont

groter is. Dus als een werknemer in de ochtend meer tijd thuis besteedt, dan is haar vraag naar een groter huis hoger. Alhoewel dit effect relatief klein kan zijn op individueel niveau, kan het effect op de lange termijn merkbaar zijn voor de hele stad. Het tegenovergestelde wordt vaak gevonden in stedelijke modellen waarin de congestie op een constant niveau wordt verondersteld gedurende de hele dag, aangezien deze modellen voorspellen dat de dichtheid van steden toeneemt door tolheffingen. Ondanks deze verschillen in resultaten zijn er overeenkomsten met andere studies die aantonen dat verbetering van het stedelijke vervoer, zoals meer capaciteit of goedkopere vormen van transport, leidt tot uitbreiding van steden.

Verkeerscongestie is voornamelijk een stedelijk probleem, vooral de congestie die gerelateerd is aan de avond- en ochtendspits die veroorzaakt wordt door woon-werkverkeer. Uit eerdere studies weten we dat transportkosten de structuur van steden beïnvloeden, en dit feit wordt ook onderschreven in dit proefschrift. Belangrijker nog is dat een meer realistische benadering van verkeerscongestie door rekening te houden met de dynamische aard van congestie laat zien dat efficiënter transport door *first-best* tolheffingen kan leiden tot grotere steden en meer welvaart, zoals bijvoorbeeld ook bereikt wordt door het vergroten van de transportcapaciteit of het voorzien in goedkopere vormen van transport. Dit is nog een reden voor stedelijke vervoersautoriteiten om het invoeren van congestieheffingen te steunen als beleidsmiddel om congestie tegen te gaan.

Hoofdstuk 4 is gericht op de welvaartseffecten van het verstrekken van verkeersinformatie aan automobilisten. Alhoewel zowel private als publieke bedrijven verkeersinformatie kunnen verstrekken aan automobilisten, is het niet duidelijk in welke mate deze marktwerking maatschappelijk voordelig is in een markt waarin het beheer van het wegennetwerk in handen is van een afzonderlijke partij. In dit hoofdstuk wordt een simpel micro-economisch model toegepast, met een elastische vraag naar reizen en stochastische transportkosten, om een endogene vraag naar verkeersinformatie af te leiden. Winstmaximaliserende prijsstrategieën van de informatieverstrekker en de wegbeheerder zijn onderling afhankelijk omdat zowel de tol als de prijs van verkeersinformatie het aantal automobilisten op de weg kan beïnvloeden, en dus de omvang van de markt en de potentiële winst.

Het blijkt dat het verstorende welvaartseffect van een monopolistische markt voor verkeersinformatie relatief klein is. Bij een evenwicht in de markt, is

de prijsstrategie van de informatieverstrekker om zich het consumentensurplus toe te eigenen van die automobilisten die reizen zelfs wanneer de vervoerskosten hoog zijn. Het monopolistische prijsverschil wordt dus herverdeeld van de consumenten naar de monopolistische informatieverstrekker, maar drijft uiteindelijk niet veel automobilisten uit de markt. De resultaten laten zien dat samenwerking tussen de beheerder van het wegennetwerk en de informatieverstrekker leidt tot een lagere gezamenlijke prijs in vergelijking met de situatie waarin beide apart opereren, omdat de winst van beide partijen onderling afhankelijk is. Het onderliggende mechanisme van dit resultaat is nauw verbonden met het gebruikelijke argument in *double-marginalization* modellen, ook al verkopen beide bedrijven direct aan de consument en zijn de twee goederen niet strikt complementair: men kan reizen zonder verkeersinformatie. Er zijn weinig redenen om private wegbeheerders te verbieden verkeersinformatie aan te bieden op hun eigen wegennet.

Informatietechnologie voor transport en vervoer, zoals verkeersinformatie voor automobilisten, lijkt een populaire manier om verbeteringen in transport door te voeren. De resultaten beschreven in dit proefschrift suggereren dat privaat aanbod van verkeersinformatie een haalbare en relatief efficiënte manier is om maatschappelijke voordelen uit dergelijke technologieën te halen, aangezien misbruik van monopolistische marktmacht niet leidt tot een grote vermindering van economische transacties zoals vaak het geval is bij een monopolistische marktstructuur. Bedrijven die verkeersinformatie verstrekken zouden aangemoedigd moeten worden om hun diensten aan te bieden zelfs in samenwerking met wegbeheerders, privaat of publiek.

Hoofdstuk 5 grijpt terug op het onderwerp telewerken en is een empirische studie naar de ruimtelijke gevolgen van telewerken. Ondanks de sterke beleidssteun voor telewerken, zetten economen vraagtekens bij de mogelijke positieve effecten als telewerken leidt tot lagere kosten voor woon-werkverkeer en werknemers op de lange termijn daardoor naar een goedkopere woonlocatie verhuizen verder van de werkplek. Een langere reisafstand, hoewel met een lagere reisfrequentie, kan potentieel het positieve effect van telewerken op congestie en luchtvervuiling teniet doen. In dit hoofdstuk wordt onderzocht of de gemiddelde afstand van woon-werkverkeer voor beroepsgroepen waarin veel mensen telewerken wordt beïnvloed door technologie. De identificatiestrategie in Hoofdstuk 5 is gericht op het testen van



dit mogelijke effect, rekening houdend met de mogelijkheid dat de causaliteit van dit effect ook tegengesteld kan verlopen, door middel van een *difference-in-difference* methode in combinatie met *propensity score matching*. Cross-sectie data uit de Nederlandse Enquête Beroepsbevolking voor 1996, toen technologie nog nauwelijks werd toegepast, en 2010, toen internet wijdverbreid was, biedt de mogelijkheid om de langetermijn causale relatie te onderzoeken tussen de toepassing van telewerken en de reisafstand naar het werk.

De resultaten laten zien dat de gemiddelde reisafstand tot het werk is toegenomen met twee kilometer tussen 1996 en 2010 voor mensen in een beroepsgroep waar een substantieel deel van de werknemers telewerkt. Een zelfde effect wordt gevonden voor beroepsgroepen waar niet aan telewerken wordt gedaan. Dit impliceert dat het invoeren van telewerken geen effect heeft op de gemiddelde reisafstand voor woon-werkverkeer. De resultaten suggereren ook dat er een afwijkend effect is van telewerk-technologie op werknemers die telewerken en op werknemers die niet telewerken binnen de beroepsgroepen waar telewerken mogelijk is. Werknemers die telewerken hebben een langere reisafstand tot het werk, maar dit effect wordt gemiddeld gezien teniet gedaan door de afname van de reisafstand voor de werknemers die niet telewerken, in vergelijking met de werknemers in beroepsgroepen waar telewerken niet mogelijk is. Een verklaring voor deze puzzel blijkt moeilijk te geven. Vanuit beleidsoptiek suggereren de resultaten in hoofdstuk 5 dat het voor beleidsmakers mogelijk is om telewerken te promoten als een middel om de negatieve effecten van reizen te beperken, wat niet het geval is als de resultaten zouden aantonen dat de gemiddelde reisafstand naar het werk hierdoor toeneemt.

Zolang er technologische vooruitgang is, is er behoefte aan analyses van de economische implicaties van deze vooruitgang voor beleidsvorming. Alleen door zorgvuldige toepassing van het volledige spectrum van beschikbare beleidsinstrumenten, zowel de traditionele als innovatieve, kan gestreefd worden naar een efficiënter transportsysteem.

The Tinbergen Institute is the Institute for Economic Research, which was founded in 1987 by the Faculties of Economics and Econometrics of the Erasmus University Rotterdam, University of Amsterdam and VU University Amsterdam. The Institute is named after the late Professor Jan Tinbergen, Dutch Nobel Prize laureate in economics in 1969. The Tinbergen Institute is located in Amsterdam and Rotterdam. The following books recently appeared in the Tinbergen Institute Research Series:

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